DEPARTMENT OF DEFENSE

DEVELOPING SCIENCE & TECHNOLOGIES LIST

SECTION 16: POSITIONING, NAVIGATION AND TIME TECHNOLOGY

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Washington, D.C.

PREFACE

A. THE MILITARILY CRITICAL TECHNOLOGIES PROGRAM (MCTP)

The MCTP supports the development and promulgation of the congressionally mandated Militarily Critical Technologies List (MCTL) and the Developing Science and Technologies List (DSTL).

Congress assigns the Secretary of Defense the responsibility of providing a list of militarily critical technologies (the MCTL) and of updating this list on an ongoing basis. The MCTL identifies technologies crucial to weapons development and has been a key element in evaluating U.S. and worldwide technological capabilities. The MCTP has provided the support for a wide range of assessments and judgments, along with technical justifications for devising U.S. and multilateral controls on exports. The DSTL, another MCTP product, identifies technologies that may enhance future military capabilities.

The MCTP technology assessment process is a continuous analytical and information-gathering process that refines information and updates existing documents to provide thorough and complete technical information. It covers the worldwide technology spectrum and provides a systematic, ongoing assessment and analysis of technologies and assigns values and parameters to these technologies.

Technology Working Groups (TWGs), which are part of this process, provide a reservoir of technical experts. TWG chairpersons continuously screen technologies and nominate items to be added or removed from the list of militarily critical technologies. TWG members are subject matter experts (SMEs) from the military Services, DoD and other federal agencies, industry, and academia. A balance is maintained between public officials and private-sector representatives. Working within an informal structure, TWG members strive to produce precise and objective analyses across dissimilar and often disparate areas. Currently, the TWGs are organized to address 20 technology areas:

Aeronautics	Information Systems
Armament and Energetic Materials	Lasers, Optics, and Imaging
Biological	Processing and Manufacturing
Biomedical	Marine Systems
Chemical	Materials and Processes
Directed Energy Systems	Nuclear Systems
Electronics	Positioning, Navigation, and Time
Energy Systems	Signature Control
Ground Combat Systems	Space Systems
Information Security	Weapons Systems

B. THE DEVELOPING SCIENCE AND TECHNOLOGIES LIST (DSTL)

The DSTL focuses on worldwide government and commercial scientific and technological capabilities that have the potential to significantly enhance or degrade US military capabilities in the future. It includes new and enabling technologies as well as those that can be retrofitted and integrated because of technological advances. It assigns values and parameters to the technologies and covers the worldwide technology spectrum.

The DSTL is oriented towards advanced research and development including science and technology. It is developed to be a reference for international cooperative technology programs. The DSTL includes basic research, applied research and advanced technology development. Separate documents contain a Glossary and a list of Acronyms and Abbreviations.

This document, DSTL Section 16: Positioning, Navigation and Time Technolog, January 2006 supersedes DSTL, Section 16, Positioning, Navigation and Time Technology, May 2000.

INTRODUCTION

A. ORGANIZATION OF THE DEVELOPING SCIENCE AND TECHNOLOGIES LIST (DSTL)

The DSTL is a documented snapshot in time of the ongoing MCTP technology assessment process. It includes text and graphic displays of technical data on individual technology data sheets.

Each section contains subsections devoted to specific technology areas. The section front matter contains the following:

- *Scope* identifies the technology groups covered in the section. Each group is covered in a separate subsection.
- *Highlights* identify the key facts in the section.
- *Overview* discusses the technology groups identified under "Scope."
- *Background* provides additional information.

Each technology group identified under Scope has a subsection that contains the following:

- *Highlights* identify the key facts found in the subsection.
- *Overview* identifies and discusses technologies listed in data sheets that follow.
- *Background* provides additional information.
- *Data Sheets,* which are the heart of the DSTL, present data on individual technologies.

B. TECHNOLOGY DATA SHEETS

The technology data sheets are of primary interest to all users. They contain the detailed parametric information that managers, R&D personnel, program managers (PMs), and operators need to execute their responsibilities.

- *Technology Parameter(s)* includes the parameter, data argument, value, and level of the technology where its technical performance would significantly advance an adversary's military capability or impair or negate a U.S. military capability.
- *Critical Materials* are those materials that are unique or enable the capability or function of the technology.
- *Unique Test, Production and Inspection Equipment* includes that type of equipment that is unique.
- *Unique Software* is software needed to produce, operate, or maintain this technology that is unique.
- *Major Commercial Applications* addresses commercial uses of this technology.
- *Affordability Issues* are those factors that make this technology an affordability issue.
- *Background* provides additional information.

SECTION 16—POSITIONING, NAVIGATION, AND TIME (PNT) TECHNOLOGY

Scope

Highlights

- PNT technology usage has doubled every 5 years since 1960, mostly because of the U.S. Global Positioning System (GPS) program and the miniaturization of electromechanical components. Future PNT usage is expected to double every 2 years because of telecommunication, automobile navigation, robotics and commercial markets inserting MEMS (micro) and ultra-cold quantum technology.
- The economic engine for PNT is from the nonmilitary commercial sector. Chip scale atomic clocks will revolutionize the dissemination of worldwide accurate time in lieu of GPS. The expanding need for more accurate position and especially precise time is a classic example of “build it and they will come.”
- Military exploitation and harnessing of three-dimensional position (latitude, longitude, and altitude) and time (POSITIME) and the use of hybrid multisensor arrays are in the embryonic stage relative to a common battlespace grid reference.
- Significant advances in PNT technologies should be anticipated from developed nations and also developing nations allowing more nontraditional manufacturing sources of PNT products.
- Future developments in ultra-cold quantum gyroscope technology may be the next post-MEMS technology or ultra-cold quantum technology, if quantum noise measurement techniques are resolved. The potential of this technology to provide unprecedented drift rates will provide a significant military capability.
- Gravity meter and gravity gradiometer arrays with accurate time sequencing, faster computer speeds, and memory advances can provide improved detection and location of submarines, mines, tunnels and mobile missile launchers. MEMS and embedded in ultra-cold quantum technology gravity and magnetometer sensors have high potential for low cost navigation sensors.
- DBRN systems will proliferate, especially for terrain and underwater navigation, using LADAR or SONAR for along track positioning and imaging sensors for cross track positioning. Correlation of data using terrain,
- Magnetic and gravity mapping data and computer techniques will improve positioning accuracies.
- The accuracy of magnetic gradiometers, utilizing either the SQUID or potassium technologies, nearly eliminates the natural geomagnetic background noise.
- Biological navigation is currently at a similar stage of development as aviation technology was during World War I. The biological five senses in robotic importance are see, hear, smell, touch, and taste.
- Without single joint programmatic authority, warfighter-robot integration will be the critical issue for most military applications. Training needs to be recognized as a major requirement for warfighter-robot combat missions.

OVERVIEW

Recent localized conflicts and the evolving role of the U.S. military in antiterrorism points to (1) the future use of more autonomous unmanned vehicles (AUVs) for precision strike and tactical combat, in addition to surveillance, targeting, and covert operations, and (2) more use of long-range, stand-off, precision and laser-guided weapons and other smart weapons, including artillery shells and munitions. To achieve supremacy will require using advanced technologies in computer processing, navigation and precise time, telecommunications, and positive combat identification sensors in a "system of systems." This capability will provide accurate locations of friendly and enemy forces, as well as the ability to collect, process, and distribute relevant data that is position and time (POSITIME) tagged across the battlespace. With concurrent training, this interactive "tactical picture" will gain U.S. forces an enormous dominant battlespace awareness, which will decrease response time and make the battlespace considerably transparent for the warfighter.[1] Included in this section are descriptions of the sensor technologies necessary to achieve autonomous and cooperative positioning, data-based referenced navigation systems, precise time and biological navigation. Situational Awareness and Combat Identification, formerly a part of Section 16, can be found in Section 10, Information Technology.

BACKGROUND

The importance of PNT technologies and their potential capabilities could be used (by friend and foe) to deliver conventional weapons, a single item (for nuclear), individually targeted remote vehicles (RVs), or a set of items to a level of accuracy appropriate to the destructive footprint of appropriate munitions. These parameters could be achieved either individually or when used as an integrated or hybrid system. Accurate positioning, attitude, pointing, and control of land, sea, air, and space vehicles are essential for effective coordination of highly mobile military forces. These capabilities directly enhance the delivery accuracy and lethality of manned and unmanned guided and unguided weapons systems. In addition, other mission requirements, such as reconnaissance and detection, require accurate velocity, motion compensation, and positioning synchronization data to maintain real-time knowledge of the enemy. Much research is being done at universities and laboratories on specific areas of autonomous robotics. However, no centralized training effort is being led to develop an integrated "teaming" of the soldier, his fellow combatants or with the robot to achieve a military objective efficiently.

1 http://www.dtic.mil/futurejointwarfare/

SECTION 16.1—INERTIAL NAVIGATION SYSTEMS AND RELATED COMPONENTS

Highlights

- Increased gyroscope and accelerometer performance, and decreases in the cost and size of inertial navigation systems (INS) technology will continue.
- Hybrid INS with embedded Global Navigation Satellite Systems (GNSS) and Data-Based Referenced Navigation (DBRN) systems will increase significantly over the next 5–10 years. The ultratight coupled integration of position and time will result in improved navigation performance and more anti-jam robustness of GNSS. These Hybrid systems will be installed on most DoD assets and even combat personnel, thereby providing a common coordinated reference system for improved battlespace awareness.
- For underwater navigation, further improvements in hybrid INS systems, particularly with underwater sonar navigation and DBRN systems, will increase covertness and accuracy without use of GNSS. This will lead to port-to-port submarine navigation capability without need to surface.
- Major reduction in manufacturing complexity, size, and cost of INS will be realized by use of microelectromechanical systems (MEMS) sensors. This will allow expanded military use of INS (for personnel, low- cost vehicles, smart artillery and ordnance, and autonomous unmanned vehicles (AUVs) and expanded commercial applications, thereby providing a larger market for more nontraditional manufacturers of inertial navigation technology.
- Future developments in ultra-cold quantum gyroscope technology may be the next post-MEMS technology, if quantum noise measurement techniques are resolved. The potential of this technology to provide unprecedented drift rates will provide a significant military capability.

OVERVIEW

An inertial navigation system (INS) is a self-contained, covert system that provides continuous estimates of some or all components of a vehicle state, such as position, velocity, acceleration, attitude, angular rate, and often guidance or steering inputs. The current major obstacle of more universal INS use is its loss of accuracy over time and high cost. Military applications include both strategic and tactical systems: missiles, AUVs, manned aircraft, satellites, aircraft carriers, submarines, surface ships, and land warfare. Targeting, surveillance, and command, control, and communications (C^3) systems require high navigation accuracy. Figures 16.1-1 and 16.1-2 address the key gyroscope and accelerometer performance requirements for these military applications, including the key commercial automotive market driver. INS technology has been enormously affected by advances in computer technology (memory and throughput), sensors, power quality, and electronics. Most current military INS uses optical gyroscopes, ring laser gyroscopes (RLG) or fiber optic gyroscopes (FOG), however MEMS gyroscopes are now being used in tactical missile applications.

BACKGROUND

An INS contains a navigation computer and a stable platform[2] composed of gyroscopes and accelerometers, generally called inertial sensors that measure angular rotation and acceleration respectively in each inertial axis. The gyroscopes maintain the stable platform aligned to inertial space. Integrating the output from an accelerometer relative to time gives speed, and integrating speed gives distance traveled. Speed is the magnitude of velocity

[2] These stable platforms are often called the inertial navigation unit, inertial measurement unit, inertial reference unit, inertial sensor assembly, or inertial sensor unit.

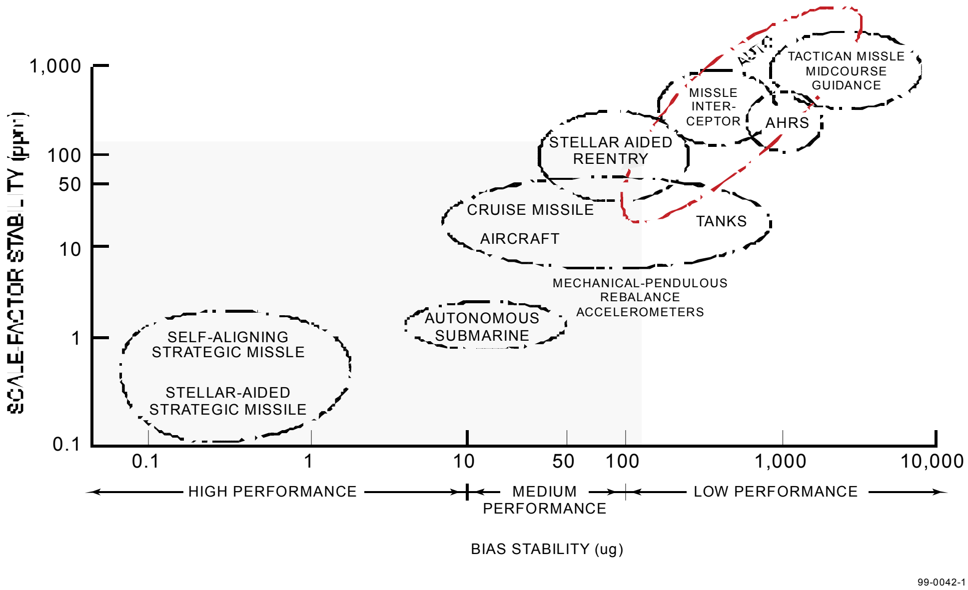

Figure 16.1-1. Accelerometer Technology Applications
(Note: Shaded area shows military performance criticality. For smart munitions surviving high shock levels is more critical.)

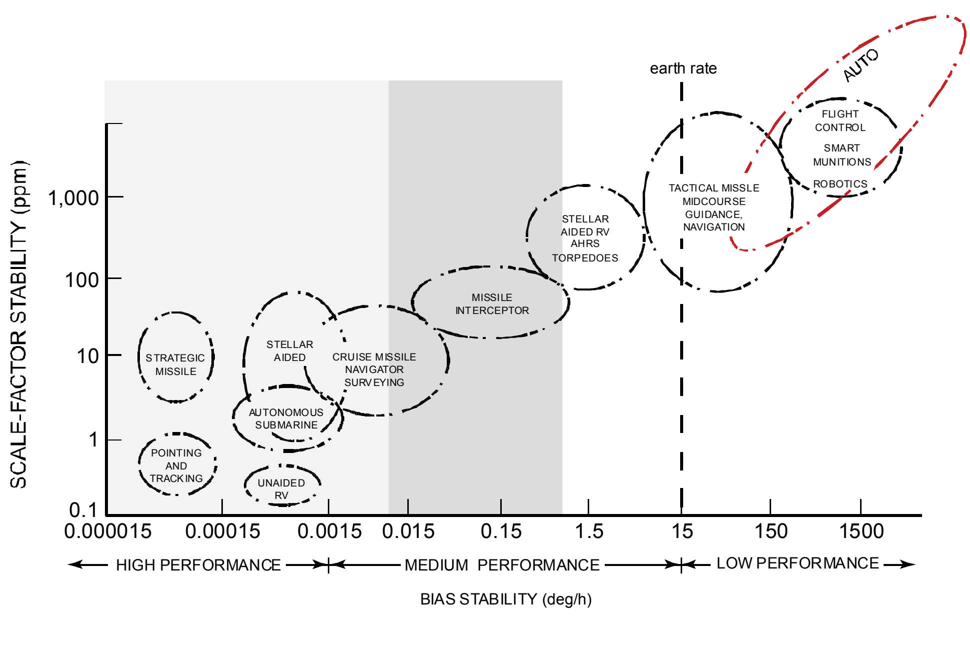

Figure 16.1-2. Gyroscope Technology Applications
(Note: Shaded area shows military performance criticality. For smart munitions surviving high shock levels is more critical.)

irrespective of direction. The gyroscopes also provide information on where the accelerations are directed, and therefore heading, speed and distance traveled, the essential ingredients for a dead reckoning navigation system.

The inertial sensors might be mounted in a set of gimbals so that they stay level in a fixed direction no matter how the vehicle moves. This is called a *gimbaled* system. As an alternative, the instruments might be attached to the vehicle, in which case they measure its motion components in the vehicle axes by transforming the measurements from the vehicle axes to the reference axes. This is called a *strapdown* system.[3]

The following definitions apply to this section:

- An inertial system is a general term that includes any system or equipment that uses gyroscopes or accelerometers that apply Newton's laws of motion to sense the Earth's rotation and vertical.
- An inertial navigation system is a special type of inertial system that provides a continuous indication of position, attitude (roll and pitch), true heading and velocity.
- Inertial equipment is made up of devices incorporating gyroscopes and/or accelerometers that provides measurements of rotation rates around three orthogonal axes or inertial acceleration along three orthogonal axes, respectively, such as Inertial Measurement Units, Attitude Heading Reference Systems, or Gyrocompasses.

[3] Anthony Lawrence, *Modern Inertial Technology,* 1998.

LIST OF DSTL TECHNOLOGY DATA SHEETS
16.1. INERTIAL NAVIGATION SYSTEMS AND RELATED COMPONENTS

DSTL DATA SHEET 16.1-1. INERTIAL NAVIGATION SYSTEMS

Technology Parameter(s)	The following level of unaided performance will significantly enhance military capabilities within the next 5 to 10 years: 1. For aircraft, vehicle, or spacecraft for attitude, guidance, and control—navigation error < 0.1 nm/hr CEP. 2. For ships—navigation error of < 1.0 nm in 30 hrs. 3. For missiles—navigation error of < 0.4 nm/hr CEP. 4. Capable of operating through shock levels greater than 1,000 g.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Components require specially designed test, calibration, or alignment equipment. Ships motion simulator.
Unique Software	Algorithms and verified data needed to exceed technology parameters. INS alignment time for moving platform and transfer alignment techniques. Algorithms for gyro compensation, Kalman filter implementations, and sensor data processing.
Major Commercial Applications	Aviation, ships, spacecraft.
Affordability Issues	Accuracy and size are cost driver. Reduced costs are attendant with strapdown systems and production base.

BACKGROUND

An inertial navigation system (INS) is a self-contained, covert system that provides continuous estimates of some or all components of a vehicle state, such as position, velocity, acceleration, attitude, angular rate, and often guidance or steering inputs. The INS is made from a navigation computer and a set of gyroscopes and accelerometers, generally called inertial sensors that measure in Newton's inertial axes. Gyroscopes measure rotation, and accelerometers measure acceleration. Integrating the output from an accelerometer gives speed, and integrating speed gives distance traveled. The gyroscopes provide information on where the accelerations are directed, and therefore heading and distance, the essential ingredients for dead reckoning, are known.

The inertial sensors might be mounted in a set of gimbals so that they (1) stay level in a fixed direction no matter how the vehicle moves, i.e., space stable INS, or (2) remains parallel to the reference ellipsoid, i.e., a local level INS. Both of these are called a *gimbaled* system. As an alternative, the inertial sensors might be attached to the vehicle, in which case they measure its motion components in the vehicle axes by transforming the measurements from the vehicle axes to the reference axes. This is called a *strapdown* system.[4]

The inertial navigation unit, inertial measurement unit, inertial reference unit, inertial sensor assembly, or inertial sensor unit are subassemblies of an inertial navigation system; a self-contained, covert system that provides continuous estimates of some or all components of a vehicle state, such as position, velocity, acceleration, attitude, angular rate, and often guidance or steering inputs.

[4] Anthony Lawrence, *Modern Inertial Technology,* 1998.

DSTL DATA SHEET 16.1-2. HYBRID INERTIAL NAVIGATION SYSTEMS (INCLUDING GNSS)

Technology Parameter(s)	The following level of performance will significantly enhance military capabilities within the next 5 to 10 years: 1. Any hybrid (the terms “hybrid” and “integrated” are the same) inertial navigation system (gimbaled or strapdown) having any of the following characteristics: a. Integrated or embedded with any single or combination of navigation/communication/optical sources [Doppler (sonar, laser, or radar), LORAN, Air Data, GNSS, or DBRN (acoustic, stellar, gravity, and magnetic databases], 3-D digital terrain maps and other geomapping data, JTIDS, EPLRS, Electro-Optics Imaging) having a position accuracy of less (better than) 1 m CEP. b. After loss of GNSS, having, for a period of up to 4 min, a position accuracy of less (better) than 1 m CEP, or a navigation drift rate of less (better) than 0.1 nmi/hr or a velocity accuracy of less than 0.1 m/s, or an azimuth accuracy of less than 0.5 arc minutes times secant of latitude.
Critical Materials	Tamper-resistant thermal-spray technology to protect components containing sensitive U.S. cryptographic logic.
Unique Test, Production, Inspection Equipment	Components that require specially designed test, calibration, or alignment equipment. GNSS receivers that require use of military-capable, signal-simulator testing systems. Systems that simulate/generate the specialized radio-frequency signal and data message structure and require the use of U.S. cryptography. Any antispoofing signal simulators.
Unique Software	Software specially designed or modified to meet technology parameters. Source code for inertial navigation systems for hybridized use. Source code, algorithms, and verified data needed to exceed technology parameters with any of following navigation data: Doppler radar or sonar, LORAN, Air Data, GNSS, or DBRN (acoustic, stellar, gravity, and magnetic databases, or 3-D digital terrain maps and other geo-mapping data). Source code for integrated avionics or other mission systems that combine sensor data and employ expert systems.
Major Commercial Applications	Aviation, ships, spacecraft, and land vehicles; rescue personnel.
Affordability Issues	Accuracy and autonomy are the key drivers. Reduced processor costs and memory will significantly reduce costs. Low power use critical for large subset of commercial applications.

BACKGROUND

Hybrid INS/GNSS systems combine the best features of different navigation systems to provide an autonomous, covert, and nonjammable system that will locate our forces and, when used with other technologies, can locate enemy troops and targets. The reason for this is that while INS navigation accuracy varies as a function of time, GNSS navigation performance is not time dependent, and therefore bounds the INS error. GNSS signals can also be jammed and INS cannot be jammed.

Other hybrid INS/navigation systems include Doppler (Sonar, Laser, Radar), LORAN, or DBRN particularly terrain-aided database. All these navigation technologies are not affected by time. Integrating any combination of these systems with an INS, results in a system called a *hybrid inertial navigation system* that provides a very accurate navigation system independent of time. The INS provides a "flywheel" effect for continuous accurate navigation, even when these other navigation signals are lost (intentionally or not).

Communication systems such as JTIDS and EPLRS provide a relative navigation capability within the network, thereby bounding the INS errors. Many other technologies can be integrated with inertial equipment, but are too numerous to include. Below are just a few:

- *Hybrid Inertial/Optics*—Inertial sensors have large measurement uncertainty at slow motion and lower relative uncertainty at high velocity. Vision-based navigation systems can use passive landmarks, but they are more computationally demanding and often exhibit erroneous behavior due to occlusion or numerical instability. Inertial sensors are completely passive, requiring no external devices or targets.

  http://paloma.isr.uc.pt/icar/workshop/inervis/INERVIS2003.pdf

- *Hybrid Inertial/Laser*—Primarily used for surveying, this integration provides very accurate pointing reference. An example is its use in laser mapping. http://www.gisdevelopment.net/aars/acrs/2000/ps1/ps110.shtml

- *Hybrid Inertial/Doppler (Radar or Sonar)*—For underwater navigation, the inertial equipment or INS provides the heading reference source with a Doppler velocity log (DVL) to provide a seafloor navigation capability. The Doppler velocity can also be used as a reference velocity for INS damping. http://www.kearfott.com/seadevil.pdf

- *Hybrid Inertial/ Magnetometers*—Research for a vehicle intelligent navigation system using array magnetometers to sense magnetic markers embedded in the roadway with approximate 1.0 cm accuracy. Combined with GNSS and INS this provides a triple redundancy navigation system whether or not GNSS or magnetometer measurements are available. For Magnetic DBRN systems refer to Data Sheet 16.3-14.

  http://www.path.berkeley.edu/PATH/General/WhatsNew/IM9.4.pdf

- *Hybrid Inertial/Gravimeters*—Hybrid Inertial Gravimeters utilizes the combination of DGPS data and the inertial sensor data (gyros and accelerometers contained within the Gravity-Gradiometer). This combination produces exceptionally accurate navigation data, which is used for both position location and to provide Eotvos corrections for the gravity data. For Gravity DBRN systems refer to Data Sheet 16.3-15.

  http://www.bellgeo.com/tech/measurements.html

  http://internal.physics.uwa.edu.au/~frank/NewScientist/gravity.html

DSTL DATA SHEET 16.1-3. GYRO ASTRO-TRACKING DEVICES OR STAR TRACKERS

Technology Parameter(s)	The following level of performance will significantly enhance military capabilities within the next 5 to 10 years: 1. Navigation error < 0.1 nmph CEP. 2. Attitude and Pointing accuracy < 5 arc seconds. 3. In addition, developing technology will be lighter and less expensive.
Critical Materials	Optics.
Unique Test, Production, Inspection Equipment	Components require specially designed test, calibration, or alignment equipment including clock accuracy of a microsecond per 24 hours. Star simulators required.
Unique Software	Algorithms and verified data needed to exceed technology parameters. Source code for combining an inertial navigation system with a gyro astro tracker is unique. Gyro astro tracker stabilization requires accurate initialization and reference data from an inertial navigation system.
Major Commercial Applications	Spacecraft stabilization and basic geodetic research.
Affordability	Miniaturization and larger volume markets will significantly reduce costs.

BACKGROUND

Gyro astro-tracking devices or star trackers are a type of telescope on a stable (gyroscopic) platform with an optical sensor at its focus. These sensors can be precisely pointed at a star whose location (e.g., right ascension and declination) is known. Tracking multiple stars simultaneously can determine the vehicle's (see Figure 16.1-3) attitude (2 stars required) and position (3 or more stars required) using the triangulation method similar to GNSS satellites. Changes in position can determine navigation parameters: direction and speed. For Stellar DBRN systems refer to Data Sheet 16.3-11.

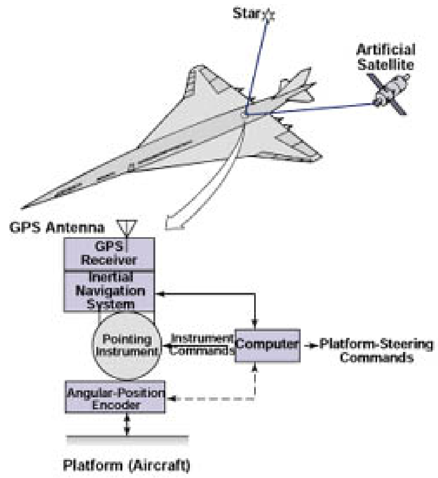

Figure 16.1-3. Illustration of a Pointing Instrument (Star Tracker) integrated in an aircraft[5]

5 http://www.nasatech.com/Briefs/Feb01/ARC14060.html

DSTL DATA SHEET 16.1-4. AZIMUTH (NORTH-POINTING) DETERMINATION SYSTEMS (NON-CELESTIAL DEVICES)

Technology Parameter(s)	The following performance will have the potential to significantly enhance military capabilities within the next 5 to 10 years: 1. Providing an azimuth or north pointing accuracy of less (better) than 0.5 arc minute times secant of latitude.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Components require specially designed test, calibration, or alignment equipment.
Unique Software	Algorithms and verified data needed for compensation.
Major Commercial Applications	Satellite communications; bore sighting, geodesy, surveying, and construction.
Affordability Issues	Not an issue.

BACKGROUND

Azimuth or north-pointing determination systems, other than celestial devices, use gyroscopes to precisely determine the orientation of the vehicle with respect to true geographic north. For pointing systems using celestial or star tracking technology refer to Data Sheet 16.1-3.

There are different types of azimuth, or north-pointing systems that meet this capability. Inertial navigation systems (INS) are addressed in Data Sheet 16.1. This data sheet only addresses the following inertial equipment: (1) inertial measurement units (IMU), (2) attitude heading reference systems (AHRS), and (3) gyrocompasses or equivalent. Fluxgate compasses are addressed in Section 16.4.

These azimuth or north-pointing determination systems incorporate gyroscopes and/or accelerometers that provide measurements of rotation rates around three orthogonal axes or inertial acceleration along three orthogonal axes. An IMU provides angular rate of change on each axis. An AHRS or gyrocompass provides attitude and magnetic heading, but does not provide a complete navigation solution. It may provide velocity, angular rate, and acceleration data in addition to attitude and heading. All these systems may be combined into hybrid systems to compute azimuth and other navigation functions.

The inertial sensors might be mounted in a set of gimbals so that they stay level in a fixed direction no matter how the vehicle moves. This is called a *gimbaled* system. As an alternative, the instruments might be attached to the vehicle, in which case they measure its motion components in the vehicle axes by transforming the measurements from the vehicle axes to the reference axes. This is called a *strapdown* system.

DSTL DATA SHEET 16.1-5. MICROELECTROMECHANICAL SYSTEM (MEMS) INERTIAL MEASUREMENT UNIT (IMU) AND IMU ON-A-CHIP

Technology Parameter(s)	The following level of performance will significantly enhance military capabilities within the next 5 to 10 years: 1. Gyro rate bias stability of less than 0.3 deg/hr, 1σ. 2. Gyro range greater than ± 1,440 deg/sec. 3. Accelerometer bias stability of less (better) than 130 µg, 1σ. 4. Accelerometer scale factor of less (better) than 130 ppm, 1σ. 5. When integrated with navigation computer provides a navigation error less (better) than 5 nm/hr. 6. Operation with total IMU power consumption < 0.25 Watt. 7. Capable of operating through 1,000 g and surviving a shock greater than 20,000 g.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Specially designed test calibration, or alignment equipment.
Unique Software	Algorithms and verified data needed to exceed technology parameters. Algorithms for alignment time on a moving platform and transfer alignment techniques. Algorithms for gyro compensation, Kalman filter implementations, and sensor data processing when integrated with GNSS and DBRN systems.
Major Commercial Applications	Automotive stability and robotics.
Affordability Issues	Reduced costs are attendant with production base.

BACKGROUND

An inertial measurement unit (IMU) is a device incorporating gyroscopes and/or accelerometers that provides measurements of rotation rates around three orthogonal axes or inertial acceleration along three orthogonal axes, respectively. This system may also be combined into hybrid systems to complete the navigation function. The inertial sensors might be mounted in a set of gimbals so that they (1) stay level in a fixed direction no matter how the vehicle moves, i.e., space stable INS, or (2) remains parallel to the reference ellipsoid, i.e., a local level INS. Both of these are called a *gimbaled* system. As an alternative, the instruments might be attached to the vehicle, in which case they measure its motion components in the vehicle axes by transforming the measurements from the vehicle axes to the reference axes. This is called a *strapdown* system. All Microelectromechanical Systems (MEMS) IMUs are inherently strapdown systems.

The IMU (or sometimes called inertial reference unit, inertial sensor assembly, or inertial sensor unit) is a critical subassembly of an INS. The IMU is a self-contained, covert system that provides continuous estimates of a vehicle's angular and linear orientation in inertial space. When integrated with a processor, it can provide a vehicle's position, velocity, and attitude by means of the double integration of the outputs of accelerometers.

DSTL DATA SHEET 16.1-6. MICROELECTROMECHANICAL SYSTEM (MEMS) INERTIAL MEASUREMENT UNIT (ACCELEROMETERS ONLY)

Technology Parameter(s)	The following level of performance will significantly enhance military capabilities within the next 5 to 10 years: 1. Any all-accelerometer MEMS inertial measurement unit that provides both linear and angular rate sensing having the following characteristics: a. Linear acceleration measurement—bias stability of less (better) than 130 μg or a scale factor stability of less (better) than 130 ppm. b. Angular rate measurement—an equivalent drift-rate stability of less (better) than 0.5 deg/hr. c. Capable of operating through shock levels of 1,000 g and surviving shock levels greater than 20,000 g.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Specially designed test, calibration, or alignment equipment.
Unique Software	Algorithms and verified data needed to exceed military critical parameters. Error compensation for environmental effects and technology characteristics.
Major Commercial Applications	Automotive stability and robotics.
Affordability Issues	None identified.

BACKGROUND

A microelectromechanical systems (MEMS) inertial measurement unit (IMU) provides three axes of acceleration with a combination of multi-axis angular and/or linear accelerometers. Taking the difference between the accelerometer outputs of the inertial and gravitational accelerations from the rotation-induced (centripetal and tangential) accelerations, simplifies the kinematic computation of angular motions. Compared with a conventional three gyros and three accelerometers IMU, the design reduces the standard deviation of the estimates of translational displacements by 29.3 percent in each principal axis and those of the Euler orientation parameters at least 99 percent in each axis.[6]

[6] W.Ang, etal., IEEE Paper, Design of All-Accelerometer Inertial Measurement Unit for Tremor Sensing in Hand-held Microsurgical Instrument. http://www.ri.cmu.edu/pubs/pub_4499.html#abstract.

DSTL DATA SHEET 16.1-7. RING LASER GYROSCOPES (RLG)

Technology Parameter(s)	The following level of performance will significantly enhance military capabilities within the next 5 to 10 years: 1. Drift rate stability of < 0.0025 deg/hr. 2. Capable of surviving shock levels greater than 100 g.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Scatterometer accuracy of 10 ppm or less (better). Profilometer accuracy of 5 Å or less (better).
Unique Software	Algorithms and verified data needed to exceed technology parameters. Error compensation for environmental effects and differing technology characteristics.
Major Commercial Applications	Aviation, ships, spacecraft, and land vehicles.
Affordability Issues	High cost for initial national capability because clean rooms and ultra-clean, high-vacuum equipment are required. Miniaturization and larger volume markets will significantly reduce costs

BACKGROUND

Invented in the 1960s, the ring-laser gyroscope is an active-resonator optical gyroscope. A laser, the optical oscillator, is used as the light source. When used in a Fabry-Perot resonator with three or more mirrors making the light circulate through an enclosed-glass, waveguide medium, a beam splitter is used to provide clockwise and counterclockwise light beams. Both clockwise and counterclockwise waves are generated; these resonate when the path perimeter is an integral number of wavelengths, and the two waves form a standing-wave pattern. Such a laser is called a ring laser.

As the ring-laser gyroscope is rotated about an axis normal to the resonator plane, the difference in transit time (or frequency shift) of the light beam traveling in opposite directions is proportional to the rotation rate. This is called the Sagnac effect.[7] Ring-laser gyroscopes are replacing conventional spinning-mass gyroscopes in many inertial navigation system applications because of their stability, high accuracy, high reliability, and low costs.

[7] Anthony Lawrence, *Modern Inertial Technology,* 1998.

DSTL DATA SHEET 16.1-8. FIBER-OPTIC GYROSCOPES (FOG)

Technology Parameter(s)	The following level of performance will significantly enhance military capabilities within the next 5 to 10 years: 1. Drift rate stability of < 0.0025 deg/hr. 2. ARW of 0.0035 degree per square root-hour. 3. Capable of surviving shock levels greater than 100 g.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Components require specially designed test, calibration, or alignment equipment. Fiber-winding machines.
Unique Software	Algorithms and verified data needed to exceed technology parameters. Error compensation for environmental effects and differing technology characteristics.
Major Commercial Applications	Aviation, ships, land and space vehicles, robotics, manufacturing, and stability reference (cameras, and telescopes).
Affordability Issues	Use of polarization-maintaining fiber is a cost driver; however, alternatives exist. Miniaturization and larger volume markets will significantly reduce costs.

BACKGROUND

Like the ring laser gyroscope, the fiber-optic gyroscope was invented in the 1960s, but developed more slowly. Its development tracked the communications industry light source and optical fiber developments. A fiber-optic gyroscope uses the Sagnac effect to determine rotation rate. The Sagnac effect results from the counter propagation of light beams in an optical waveguide consisting of a coil of optical fiber, where the number of turns and diameter affect the accuracy of rotation-rate measurement. The difference of frequency is the optical reciprocity between clockwise and counterclockwise paths of the light beams. Rotation normal to the waveguide upsets the symmetry, which is then photoelectronically detected and processed to provide an indication of rotation rate.

The fiber-optic gyroscope is less expensive, lighter, and smaller than the ring laser gyroscope, and it may have a longer life and be more rugged. While the ring laser gyroscope blazed the trail (of optical gyroscopes) by demonstrating high performance and very long life, the fiber-optic gyroscope is just now being used in guidance-and-control systems, where it is challenging the ring laser gyroscope. In fact, the fiber-optic gyroscope has already displaced the ring laser gyroscope in some applications where gyro drift of 1 deg/h is acceptable.[8]

[8] Anthony Lawrence, *Modern Inertial Technology,* 1998.

DSTL DATA SHEET 16.1-9. HEMISPHERIC RESONATOR GYROSCOPES (HRG)

Technology Parameter(s)	The following level of performance will significantly enhance military capabilities within the next 5 to 10 years: 1. Drift rate stability less (better) than 0.0001 deg/hr. 2. Capable of surviving shock levels exceeding 100 g. 3. Manufacture costs similar to RLG or FOG.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Algorithms and verified data needed to exceed technology parameters. Error compensation for environmental effects and differing technology characteristics.
Major Commercial Applications	None identified.
Affordability Issues	Extremely costly because of low production quantities; cost decreases as production increases.

BACKGROUND

The hemispheric resonator gyroscope (HRG) is a fused-quartz hemispheric vibrating shell supported by a stem along a diameter, like a wine glass with its stem continued into the bowl. The HRG shell is electrostatically excited at its natural frequency by an alternating current (AC) signal applied to fixed electrodes on the case. A servo system drives the shell to resonance and maintains the oscillating wave amplitude constant. Because the internal damping of quartz is so low and the enclosure is evacuated, little energy needs to be supplied to maintain resonance. As the gyro is rotated about its axis, the change in the oscillating wave amplitude, detected by the capacitive pick-offs, is directly proportional to the angular movement of the resonator. The HRG is expensive to manufacture because its performance comes from the precise manufacturing of the shell and housing and the high vacuum sealing.[9]

[9] Anthony Lawrence, *Modern Inertial Technology,* 1998.

DSTL DATA SHEET 16.1-10. MICROELETROMECHANICAL SYSTEMS (MEMS) GYROSCOPES

Technology Parameter(s)	The following level of performance will significantly enhance military capabilities within the next 5 to 10 years: 1. Drift rate stability of < 1 deg/hr. 2. Scale Factor error < 100 ppm. 3. Perform through shock levels of 1,000 g, and survive shock levels in excess of 20,000 g. 4. Power consumption < 50 mW.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Specially designed test, calibration, or alignment equipment. Gyroscope axis alignment fixture. The fabrication process relies on commonly available semiconductor process equipment, including high-precision lithography, ion milling, plasma arc, and electronic-sputtering production equipment.
Unique Software	Algorithms and verified data needed to exceed technology parameters. Error compensation for environmental effects and differing technology characteristics.
Major Commercial Applications	Vehicle control and robotics.
Affordability Issues	Miniaturization will increase application of this technology. Larger volume markets will significantly reduce costs.

BACKGROUND

A MEMS gyroscope is usually designed as an electromechanically driven resonator, often fabricated out of a single piece of quartz or silicon. Such gyroscopes operate in accordance with the dynamic theory that when an angle rate is applied to a body, a Coriolis force is generated. When this angle rate is applied to the axis of a resonating tuning folk, its prongs receive a Coriolis force proportional to the applied angular rate. This force can be measured capacitively (silicon) or piezoelectrically (quartz).[10]

Many manufacturers are developing these MEMS gyroscopes to reduce the cost of these sensors.

10 Anthony Lawrence, *Modern Inertial Technology,* 1998.

DATA SHEET 16.1-11. MICROELECTROMECHANICAL SYSTEMS (MEMS) LINEAR ACCELEROMETERS

Technology Parameter(s)	The following level of performance will significantly enhance military capabilities within the next 5 to 10 years: 1. Bias stability of 130 μg, or scale factor stability of 130 ppm. 2. Capable of operating through a shock of 1,000 g and surviving a shock level greater than 20,000 g.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Specially designed test, calibration, or alignment equipment. Accelerometer axis-alignment stations. The fabrication process relies on commonly available semi-conductor process equipment, including high-precision lithography, ion-milling, plasma-arc, and electronic-sputtering production equipment.
Unique Software	Algorithms and verified data needed to exceed technology parameters. Error compensation for environmental effects and technology characteristics.
Major Commercial Applications	Safety air bags and dynamic vehicle control.
Affordability Issues	None identified.

BACKGROUND

The microelectronics field has made pure single-crystal silicon readily available, and silicon has excellent mechanical properties: (1) harder than most metals, (2) higher elastic limits in both tension and compression than steel, and (3) negligibly small hysteresis and virtually infinite fatigue life. By using an anistropic-etching process, it can be made into microscopically small devices, including accelerometers.

There are many designs of silicon accelerometers, from a simple pendulum to a tuning fork. There are numerous other types.[11] This is a relatively new technology area. MEMS sensors are one-tenth the cost of the electromechanical sensors they replace. This reduced cost will dramatically change the inertial sensor business, just as integrated circuits changed electronics.[12]

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11 Types of accelerometers: http://zone.ni.com/devzone/conceptd.nsf/webmain/642BA974BEC02CF68625684300758292?OpenDocument.

12 Anthony Lawrence, *Modern Inertial Technology,* 1998.

DSTL DATA SHEET 16.1-12. NANOELECTROMECHANICAL SYSTEMS (NEMS) LINEAR ACCELEROMETERS

Technology Parameter(s)	The following level of performance will significantly enhance military capabilities within the next 5 to 10 years: 1. Ability to detect a 10-nanometer movement and a size less than 500 nanometers^2. 2. Capable of surviving a shock level greater than 100,000 g.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Algorithms and verified data needed to exceed technology parameters. Error compensation for environmental effects.
Major Commercial Applications	Safety air bags and dynamic vehicle control.
Affordability Issues	Will result in a linear accelerometer 1/100th the cost of similar MEMS sensors.

BACKGROUND

The nanoelectromechanical systems (NEMS) linear accelerometers are a new technology area, using optics to sense microscopic-level motion. Using comb-like polysilicon structures laid parallel at distances less than 300 nanometers to each other enables detection of 10-nanometer movement. These devices use previous recognized property of optics: light diffracted by tiny gratings that move very small lateral distances prompt a relatively large, easily measured change in the reflection of bright light. This is a relatively new technology area that will result in a linear accelerometer 1/1000th the size of similar MEMS sensors, at 1/100th the cost. This reduced cost will dramatically change the inertial sensor business, just as MEMS did with traditional gyroscopes.[13]

[13] *Aviation Week & Space Technology*, page 17, October 18, 2004.

DSTL DATA SHEET 16.1-13. SUPERFLUID QUANTUM GYROSCOPES

Technology Parameter(s)	The following technology goal within the next 5 to 10 years: 1. Miniaturized closed-cycle liquid helium refrigeration systems, including advances in Dewar technology. The following level of gyroscope performance will significantly enhance military capabilities within the next 10 to 15 years: 1. Gyroscope bias < 500 μdeg/hr.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Specially designed test, calibration, or alignment equipment; accelerometer axis align stations.
Unique Software	Algorithms and verified data needed to exceed technology parameters. Error compensation for environmental effects and technology characteristics.
Major Commercial Applications	Initial applications will be in spacecraft and space telescopes.
Affordability	Miniaturization and larger volume markets will significantly reduce costs.

BACKGROUND

Helium, when cooled to below 1 degree Kelvin, becomes a special type of liquid called a superfluid; this liquid has no viscosity and has the novel property that its circulation is quantized. In other words, the flow of liquid around a loop must occur in integer multiples of the mass of the helium atom thereby making the system a nominal inertial reference frame. Researchers have constructed ring-like structures that allow them to observe the flow of mass around a loop, thereby determining how the structure is rotating around the inertial frame of the helium contained within. Initial experiments using a few cm^2 loop lying stationary on a table was able to measure the rotation of the Earth (approx. 15 deg/hour) to an accuracy of 99.5 percent. There are clear research paths to obtain 100 times the sensitivity of the best gyroscopes now available.[14]

[14] Association for the Advancement of Science, *A New Spin on Gyroscopes*, April 1997.

DSTL DATA SHEET 16.1-14. ATOM INTERFEROMETER INERTIAL SENSORS

Technology Parameter(s)	The following performance levels will likely be reached within the next 5 to 10 years: 1. Accelerometer bias of < 500 ng, scale factor stability < 300 ppm. 2. Gyroscope bias < 500 μdeg/hr. Within the next 10 to 15 years, the following navigation performance levels are possible: 1. Navigation drift rates < 100 m/hr. 2. Integrated system volume less than one cubic meter.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Specially designed test, calibration, or alignment equipment; accelerometer axis align stations.
Unique Software	Algorithms and verified data needed to exceed technology parameters. Error compensation for environmental effects.
Major Commercial Applications	Initial applications: gravity sensors. Long range: navigation systems for ships, aircraft, and spacecraft.
Affordability Issues	None identified.

BACKGROUND

Atom interferometers, much like their optical analogs, utilize interference between two coherent waves that have propagated along different paths; however, the interference in an atom interferometer arises from the wave-like properties of the atoms themselves. The typical wavelength of matter waves is much smaller than that of visible light. While this makes the detection of the matter wave interference more difficult, it also enables higher resolution measurements than may be made with optical interferometers. Additionally, matter waves have an associated mass, and are therefore sensitive to linear accelerations as well as rotations (via the Sagnac effect). Careful control of the atom interferometer configuration is needed to separate these effects. Finally, using individual atoms as effective proof masses has allowed initial laboratory accelerometers to demonstrate unprecedented scale factor stability and scale factor match between sensors. There are many types of atom interferometers that have been constructed in laboratory settings, and several appear promising for application to navigation systems; timekeeping and magnetometry are some other potential applications.

SECTION 16.2—GRAVITY METERS AND GRAVITY GRADIOMETERS

Highlights

- Uncompensated gravity disturbances are a large error source for inertial navigation system initialization and subsequent field operation. Evolving gravity models are enabling better inertial navigation system error compensation.
- Use of a worldwide gravity database based on better instrumentation and having greater computer storage and access capabilities, in conjunction with on-board gravity sensors, provides autonomous and continuous updates to inertial navigation systems, yielding accuracy or noise level comparable with projected inertial navigation system/GPS hybrid systems for short periods of time.
- Gravity meter and gravity gradiometer size will decrease with application of MEMS and NEMS technology.
- Gravity meter and gravity gradiometer arrays with accurate time sequencing, faster computer speeds, and memory advances can provide improved detection and location of submarines, mines, tunnels, and mobile missile launchers.
- An evolving technology to compute real-time gravity data from a moving research platform using the difference in acceleration data from an uncompensated inertial navigation system and the GNSS has been demonstrated.
- Another way of computing gravity, using multiple satellites, has great potential of improving Earth-related science.

OVERVIEW

This section on gravity sensors includes both gravity meters and gravity gradiometers used in either static or moving-base measurements. Every object has a distinctive gravity signature embedded in the spectrum reflected or emitted from it. These sensors can be used for detection of differing masses and for generating a worldwide gravity database that can then be used for navigation-system error compensation. Refer to Inertial Navigation Systems, Section 16.1, and to DBRN, Section 16.3, for moving-base measurements. Compensation techniques must be used to remove the noise caused by the motion (acceleration) of the system and the noise of the mass of the compensation instrumentation. This generally requires a stable reference that can be obtained using gyros. The accuracy or noise level of the system is a function of the system stability and the complexity of the mechanical, electronic, and software compensation systems.

The use of gravity sensors for geodetic measurements and detection is a dual-use application. International cooperative efforts through the International Association of Geodesy (IAG)[15] exist for comparing absolute gravity standards. Most gravity meters are relative measuring instruments of various types, including La Coste-Romberg (now Micro-g LaCoste) and Wordon gravimeters. A gradiometer in principle is immune to the effects of vertical acceleration of the platform and the velocity-dependent interactions with the rotation of Earth.

BACKGROUND

Many countries have national gravity programs for national and international geoscience requirements. For more information on land and marine gravity methods, see reference[16] or for gravity methods, see reference.[17] There

[15] http://www.gfy.ku.dk/~iag/

[16] http://www.ngdc.noaa.gov/seg/potfld/gravity;

[17] http://britannica.com/bcom/eb/article/3/0,5716,120713+6+111024,00.html

are several methods of measuring or computing gravity. For instance, an absolute measurement of gravity can be made using accurate timing of a falling weight or a swinging pendulum in a controlled environment; a relative gravity measurement can be accomplished by using a gravity meter (gravimeter) or multiple-formation flying satellites. All of these instruments have parametric outputs of the acceleration of gravity called a Galileo (Gal), where a Gal is equal to 1 cm/sec^2 (expressed in microGals or µGals).

All modern gravity meters measure the gravity component along the system axis. The gravity field, g, is a measurement of the tendency of an object to fall in the direction of the gravity vector. That is, it is the acceleration experienced by a body in the absence of other forces. Measurements of the gravity field provide data about the distribution of an attracting mass. Gravity meters are very sensitive instruments that are difficult to build and calibrate; however, they are capable of measuring fractions of Earth's gravity field to a high degree of accuracy. Some instruments can measure to an accuracy of one part per billion of Earth's gravity field.

In its simplest form, a gradiometer is a set of gravimeters separated by a fixed distance, where the gradient is the difference in field values sensed by the gravimeters. The derivative of g is the gradient of gravity. The partial spatial derivatives of the gravity vector yield the gravity gradient tensor, consisting of nine elements. The gravity vector has three spatial components (*x*, *y*, and *z*), and derivatives are taken with respect to each of the spatial directions (*x, y,* and *z*) to yield the nine components of the tensor. The gravity gradient tensor (T) is symmetric about its diagonal, so only six of the nine terms (Txx, Tyy, Tzz, Txy, Txz, Tyz) have to be specified. Likewise, satellites separated by a fixed distance tend to separate because of gravity. The signal required to maintain the fixed distance is a function of gravity and other relatively minor perturbations.

Gravity gradiometers measure these gradients of gravity with power spectral density in noise level units of Eötvös[18] squared per radian per second. The measurement of the gravity gradient tensor is required because of the complications of signal detection when the sensor is moving relative to, and in the complicated gravity field composed of, relative varying density anomalies. To further complicate the problem for the potential field, the direction of the measurements relative to Earth is critical. This requires a stable platform, such as furnished by an inertial navigation system. The gravity gradient can be measured horizontally or vertically relative to Earth's surface or its magnetic field. The horizontal vector of the gravity gradient components points in the direction of increasing gravity (i.e., in the direction of increasing mass). To further complicate the issue, there are both static and mobile gravity meters and gravity gradiometers. More costly static gravity gradiometers are used in lieu of static gravity meters because of their greater resolution, ability to measure multiple gravity vector components (Txx, Tyy, Tzz, Txy, Txz, Tyz), and better signal-to-noise ratio.

The advantage of a moving or dynamic gravity gradiometer is detection of mass differences over a wide area. For a more complete description of gravity and gravity anomalies see reference.[19]. Gravity gradiometers can be used to measure a body's gravity field (such as Earth's), which in turn has applications for detection and localization of mass distributions, covert position determination, and inertial navigation system compensation.

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18 The units of gradient, Eötvös unit (EU), are named after Roland von Eötvös. 1 EU = 10^{-6} milliGal/cm^2. The URL http://www.gfy.ku.dk/~iag/HB2000/part1/historic.htm has further information on Roland von Eötvös. In the text, Eötvös is used as the unit of measure.

19 *Applied Geophysics, Second Edition,* by Telford, Gelhart, and Sheriff, *Cambridge University Press*, 1990.

LIST OF DSTL TECHNOLOGY DATA SHEETS
16.2. GRAVITY METERS AND GRAVITY GRADIOMETERS

DSTL DATA SHEET 16.2-1. GRAVITY METERS (GRAVIMETERS)

Technology Parameter(s)	In the next 5 to 10 years: 1. Any gravity meter (gravimeter) capable of *static* operation that has an accuracy of less (better) than 10 μGal. 2. Any gravity meter (gravimeter) capable of *mobile* operation that has an accuracy of less (better) than 0.7 milliGal with a time-to-steady-state registration of less (better) than 2 min under any combination of attendant corrective compensation and motional influences. 3. Continuing development of arrays.
Critical Materials	Beryllium.
Unique Test, Production, Inspection Equipment	Test, calibration, modeling, compensation, or alignment equipment necessary to obtain mobile accuracy of less (better) than 0.1 milliGal. Accelerometer axis-alignment stations.
Unique Software	Verified data for gravity surveys and algorithms real-time gravity compensation or arrays. Specially designed software to correct motional influences.
Major Commercial Applications	Geologic mapping and resource exploration. Tunnel and buried material detection, cargo ID and weigh-in-motion.
Affordability Issues	Cost is proportional to usage. This is not a high-volume production technology, but rather a highly specialized sensor system with minimum, but critical, applications.

BACKGROUND

The Newtonian constant of gravity, G, is different from the acceleration of gravity, g. The numerical value for g at the Earth's surface is about 980 cm/sec^2. The unit of acceleration of gravity is called a Galileo (Gal) and is equal to 1 cm/sec^2. There are two methods of measuring gravity. An absolute measurement of gravity can be made using accurate timing of a falling weight or a swinging pendulum in a controlled environment. In a laboratory environment the measurement of G is the comparison of a known mass to the attraction of the Earth. A relative uncertainty for G of about 4×10^{-5} is about the current limit. Relative gravity measurements may be made in various ways. Three types of relative-gravity instruments—the torsion balance, the pendulum, and the gravity meter (or gravimeter)—have been used. All these instruments have parametric outputs of the acceleration of gravity. The use of accuracy in milliGals reflects a desire to standardize.

Gravity meters can be used in a static or dynamic (moving) base to measure variations in the gravitational field of Earth by detecting differences in weight of an object of constant mass at different points on Earth's surface. In a static environment, a gravity meter is capable of measuring Earth's gravity to a greater degree of accuracy than the dynamic (moving) gravity meter, which suffers from acceleration noise due to motion. For moving-base measurements, compensation techniques must be used to remove the noise caused by the motion (acceleration) of the system and the noise of the mass of the compensation instrumentation. This generally requires a stable reference that can be obtained using gyros. The accuracy or noise level of the system is a function of the stability of the system and the complexity of the mechanical, electronic, and software-compensation systems.

DSTL DATA SHEET 16.2-2. GRAVITY GRADIOMETERS

Technology Parameter(s)	In the next 5 to 10 years: 1. Any gravity gradiometer capable of operation on a *static* platform with a noise level of less (better) than 0.2 Eötvös squared per radian per second. 2. Any gravity gradiometer capable of operation on a *mobile* platform with a noise level of less (better) than 100 Eötvös squared per radian per second. 3. Continuing development of arrays.
Critical Materials	Beryllium.
Unique Test, Production, Inspection Equipment	Test calibration, modeling, compensation or alignment equipment necessary to obtain *static* noise level of less (better) than 1.0 Eötvös squared per radian per second or *mobile* noise level of less (better) than 300 Eötvös squared per radian per second. Accelerometer axis-alignment stations.
Unique Software	Algorithms for compensation of environmental effects, map matching, interpretation, terrain estimation, and other unique military applications. Verified data from gravity surveys and algorithms for real-time gravity compensation.
Major Commercial Applications	Geologic mapping and resource exploration. Mass detection, cargo detection, tunnel detection, and weigh in motion.
Affordability Issues	This is a highly specialized sensor system. The size of the market does not justify modification of the technology to reduce cost. If low-cost accelerometer accuracy can be dramatically improved, the military utility of gravity gradiometer arrays will increase.

BACKGROUND

A gradiometer can be thought of as an assemblage of gravity meters with some spatial separation. The difference between readings reflects the rate of change of gravity along the direction in which the meters are separated. Over the past 50 years, a single gravity meter alternately placed at two positions on a tower would measure the vertical component of the vertical gravity field. Similar measurements can be achieved for the horizontal gradients of gravity. In 1886 Baron von Eötvös announced an instrument in which two weights were suspended from a torsion fiber at unequal heights. Because the weights were separated both vertically and horizontally, they experienced different forces due to both spatial separations.

The gradients, the second partial derivatives of the gravity potential *W*, constitute the elements of *Eötvös tensor* (or gravity gradient tensor). The derivative of g is the gradient of gravity. In its simplest form, a gradiometer is a set of gravimeters separated by a fixed distance, where the gradient is the difference in field values sensed by the gravimeters. The partial spatial derivatives of the gravity vector yield the gravity gradient tensor consisting of nine elements. The gravity vector has three spatial components (*x*, *y*, and *z*) and derivatives are taken with respect to each of the spatial directions (*x*, *y*, and *z*) to yield the nine components of the tensor. The gravity gradient tensor (T) is symmetric about its diagonal, so only six of the nine terms (Txx, Tyy, Tzz, Txy, Txz, Tyz) have to be specified. The more costly *static* gradiometer is used in lieu of a gravity meter because of its greater resolution, ability to measure multiple gravity vector components (Txx, Tyy, Tzz, Txy, Txz, Tyz), and better signal-to-noise ratio.

For *moving-base* measurements, compensation techniques must be used to remove the noise caused by the motion (acceleration) of the system and the noise of the mass of the compensation instrumentation. This generally requires a stable reference that can be obtained using gyros. The accuracy or noise level of the system is a function of the stability of the system and the complexity of the mechanical, electronic, and software-compensation systems.

SECTION 16.3—RADIO AND DATA-BASED REFERENCED NAVIGATION (DBRN) SYSTEMS

Highlights

- Over the next 5-10 years, the following will impact military use of GNSS: (1) Significant commercial and military growth and dependence on GNSS for position and precise time will increase as GNSS receivers decrease in cost, weight, and power. This will also increase use of GNSS receivers in tactical mobile robot (TMR) applications; (2) International GNSS (GLONASS, Galileo, Beidou) and E-LORAN capabilities will continue to be developed as alternatives to the U.S. GPS, providing both better redundancy and integrity monitoring, and a military challenge of denying precise positioning data to enemy forces; (3) better GPS anti-jam techniques (combination of new GPS IIF and III satellites, and increased use of hybrid navigation and other techniques) will significantly reduce military issue of GPS usage in a jamming combat environment or during signal loss; and (4) improved in-door GNSS technology, using a combinations of wireless communication and GNSS pseudolites, will provide a seamless positioning and navigation capability for military operations in an urban environment.
- Over the next 5–10 years, the following will improve underwater navigation by providing a covert port-to-port submersible navigation capability without aiding by GNSS: (1) increased use of acoustic transponders anchored to seafloor will provide underwater GNSS-like positioning accuracy over a larger segment of the world's oceans; (2) increased sensor accuracy and low probability of detection techniques of seabed hybrid Doppler sonar and inertial navigation technology; and (3) underwater data-based referenced navigation (DBRN) technology, leveraged by increased mapping of the world's oceans.
- DBRN systems will proliferate, especially for terrain navigation, using LADAR for along track positioning and imaging sensors for cross track positioning. Correlation of data using improved mapping data and computer techniques will improve positioning accuracies.

OVERVIEW

This section covers the following:

1. Radio positioning and navigation systems such as Global Navigation Satellite Systems (GNSS) and Enhanced Long Range Navigation (E-LORAN). For GNSS satellites, transmitters, and supporting ground equipment refer to Section 19, Space Systems Technology.
2. Hybrid or integrated GNSS with other navigation systems (E-LORAN, Doppler radar and sonar, data-based referenced navigation systems (bathymetric, terrain, gravity and magnetic)) are included in this section. For hybrid GNSS and inertial systems refer to Section 16.1.
3. Active Doppler radar and sonar navigation systems, passive acoustic navigation systems and imaging navigation systems, RF vision navigation systems. Autonomous stereovision navigation systems are discussed in Section 16.6.

Data-based referenced navigation systems and data sources.

BACKGROUND

GPS is the current worldwide standard for Positioning, Navigation, and Time (PNT) dissemination, and below is a list of key historical GPS events and their impact on other radio navigation systems. Included are events that had a significant impact on the movement of the GPS from a unique military capability to a worldwide standard.

Key GPS Historical Events[20]

1959 TRANSIT, the first operational satellite-based navigation system, is developed by Johns Hopkins Applied Physics Laboratory. The system was originally intended to support the U.S. Navy's ballistic submarine fleet.

1967 Timation, a Navy satellite system, is developed at the NRL for advancing the development of high-stability clocks, time-transfer capability, and 2-D navigation. The first Timation satellite is launched in May 1967.

1974 DoD determines need for a joint tri-Service program, consolidating various concepts into a single comprehensive system known as the Defense Navigation Satellite System (DNSS). The new system is to be developed by a Joint Program Office (JPO). The first DNSS (now called NAVSTAR) is launched in 1974.

1983 Following the Soviet downing of Korean Air Flight 007, President Reagan offers to make GPS (previously NAVSTAR) available for use by civilian aircraft. This marks the beginning of the spread of GPS technology from military to civilian aircraft.

1990 DoD activates selective availability (S/A), the purposeful degradation in GPS navigation accuracy, to no less than 100 meters for non-DoD users.

1991 The United States revises export regulations, making a clear delineation between military and civil GPS receivers.

1992 The United States offers to make GPS available to the international community. President Clinton reaffirms this in 1995.

1993 The Secretary of Defense formally declares initial operational capability of GPS. No longer a developmental system GPS is capable of sustaining the 100-meter accuracy and continuous worldwide availability.

1994 The Federal Aviation Administration (FAA) approves GPS for use as a stand-alone navigation aid for all phases of flight through non-precision approach. The FAA also announces the implementation of the Wide Area Augmentation System (WAAS) for the improvement of GPS integrity and availability for civil users in all phases of flight.

1995 DoD declares full operational capability of GPS. International Civil Aviation Organization (ICAO) endorses the GNSS as the core system for international use and cancels the requirement for the Microwave Landing System.

1996 President Clinton signs Presidential Directive NSTC–6, which states intention to discontinue use of S/A by 2006.

1997 Omega ceases operation as a navigation, positioning, and timing system on 30 September.

1999 Federal Radionavigation Plan removed firm date for demise of LORAN. The Interagency GPS Executive Board (IGEB) prepared national GPS plan to support global PNT services to users through an optimized system architecture consisting of GPS and augmentations to GPS.

2000 May 2000, President Clinton announces the discontinuance of GPS S/A. Presidential Directive authorized DoD to turn selective availability off resulting in 10-meter accuracy worldwide for all commercial users. The United States begins to develop a new GPS ranging signal for exclusive use by the military; the signal is known as the Military-Unique (MU) signal or M-Code (military-code).

2002 The United States starts a technical dialogue with certain member states of the European Union (EU) on signal compatibility matters between the GPS and the evolving Galileo global navigation satellite system (GNSS) design and intended use.

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[20] Scott Pace et al., "The Global Positioning System, Assessing National Policies," RAND Corporation, 1995.

2002 The DoD asks the USAF and NSA to revisit the M-code design to investigate a new security architecture not based on the use of communication security (COMSEC). The security architecture is known as the Protection of Navigation (PRONAV) concept.

2003 FAA declared Wide Area Augmentation System (WAAS) operational.

2004 The United States and the EU signed a 10-year study effort to share, review and exchange information between GPS and Galileo. Russia and United States sign agreement to cooperate on matters of civil satellite-based navigation. The United States implemented guidance and implementation actions for space-based positioning, navigation and timing programs. A new U.S. space-based positioning, navigation, and timing policy was authorized by President Bush on 8 December 2004. http://www.navcen.uscg.gov/cgsic/geninfo/FactSheet.pdf.

2005 Launch of an M-code capable GPS satellite. Japan announces plans to establish its own global positioning satellite system with launches in 2008-2009. The system would be operated in cooperation with the United States GPS. The Interagency GPS Executive Board (IGEB) was renamed the National Space-Based Positioning, Navigation, and Timing (PNT) Executive Committee.

LIST OF DSTL TECHNOLOGY DATA SHEETS
16.3. RADIO AND DATA-BASED REFERENCED NAVIGATION SYSTEMS

Radio Positioning and Navigation Systems

Other Navigation Systems and Sensors

Data-Based Referenced Navigation

DSTL DATA SHEET 16.3-1. GLOBAL NAVIGATION SATELLITE SYSTEM RECEIVERS (INCLUDING GPS-ON-A-CHIP)

Technology Parameter(s)	In next 5 to 10 years, the following will have the potential to significantly enhance or degrade U.S. military capabilities: 1. Most GNSS receivers will be hybrid GPS + GLONASS + Galileo capable with 30+ channels. 2. Significant improvements in antijam capability both from satellite signal transmission and receiver and antenna technology. 3. Performance improvements: a. Positioning of < 0.3 m 50% SEP. b. Timing of < 100 picosecond. c. Velocity of < 0.1 m/s. 4. GPS on a chip will: a. Integrate GPS/Galileo to provide positioning error of less than 1 m. b. Ability to track 30 satellites. c. Receiver power consumption: < 1 mW. d. Signal and bandwidth processing power > 10X current commercial GPS receivers. e. Size < 1 mm × 1 mm × 1 mm.
Critical Materials	Tamper-resistant thermal-spray technology to protect components containing sensitive U.S. cryptographic logic. Matched substrate material thermo conductivity, heat transfer, and strength.
Unique Test, Production, Inspection Equipment	Systems that simulate or generate the specialized radio frequency signal and data message structure and require the use of U.S. cryptography. Antispoofing signal simulators with less (better) than 28 ns measurement capability; electronic counter-countermeasures (ECCM) or interference resistance receivers.
Unique Software	Algorithms that contain U.S. cryptographic logic and other signal-protection and signal-prevention techniques. Controls for input/output ports that transfer classified national-security information. Computer-aided engineering (CAE) and automatic terrain following (ATF) software for multichip-module design and development. Spread-spectrum technology. Encrypted algorithms and verified data.
Major Commercial Applications	Ground-vehicle navigation, ship and submersible navigation, aircraft navigation, space-vehicle navigation, and surveying. DoD has exclusive access to corrected U.S. GPS pseudorange, delta range, and ephemeris data. Cellular phone location and child locator system.
Affordability Issues	Accuracy and autonomy are the key drivers. Reduced processor costs and memory will significantly reduce costs.

BACKGROUND

GNSS are satellite-based radio navigation systems that enable an unlimited number of users to do all-weather 3-D positioning, velocity measuring, and timing anywhere in the world or near-Earth space. Currently, the only two

GNSS are the U.S. GPS and Russia's GLONASS. In the next 5–10 years a new GNSS being developed by the European Union may become operational. It is called Galileo.

Normally, a constellation of 24 satellites defines a GNSS, but it can have more or less satellites. Each satellite acts as reference points from which GNSS receivers on the ground "triangulate" their position. By measuring the travel time of signals transmitted from the satellites, a GNSS receiver on the ground can determine its distance from each satellite. With distance measurements from at least four different satellites the receiver can calculate its position.[21]

Through the use of advanced, high-density radio frequency and multichip-module technology, it is currently possible to fabricate a "GPS Receiver on a Chip." The market driving this technology is wireless communications because the FCC has mandated that all cellular phones identify their location to within 125 meters for 911 emergency calls.

A new U.S. space-based positioning, navigation, and timing policy was authorized by President Bush on 8 December 2004. http://www.navcen.uscg.gov/cgsic/geninfo/FactSheet.pdf

For more on information on GNSS refer to Section 19, Space Systems Technology.

21 *Differential GPS Explained,* Trimble, 1993.

DSTL DATA SHEET 16.3-2. DIFFERENTIAL GLOBAL NAVIGATION SATELLITE SYSTEM RECEIVERS

Technology Parameter(s)	In the next 5 to 10 years, the following will have the potential to significantly enhance or degrade U.S. military capabilities: 1. Most GNSS receivers will include DGNSS capability with accuracy less than 0.3 meter. 2. DGNSS will be available on all continents including Antarctica. 3. Lighter and less expensive.
Critical Materials	Tamper-resistant thermal-spray technology to protect components containing sensitive U.S. cryptographic logic.
Unique Test, Production, Inspection Equipment	Algorithms including classified, encrypted algorithms and verified data; differential techniques that provide accuracy of < 0.3 m.
Unique Software	Algorithms including classified, encrypted algorithms and verified data needed to exceed military critical technology parameters; differential techniques that provide accuracy of < 0.3 meter. Algorithms that handle corrected pseudorange, delta range, and satellite start/stop position (corrected ephemeris) data, and the source code for combining INS with GPS. This includes ultra-tight coupling of GPS/INS and map matching software.
Major Commercial Applications	Ground-vehicle navigation, ship navigation, aircraft navigation, and surveying.
Affordability Issues	Accuracy and autonomy are the key cost drivers.

BACKGROUND

There are essentially two types of differential GNSS (DGNSS) services: wide area and local area.

- Wide area services combine data from a number of reference stations and provide corrections over an entire region. The accuracy is largely uniform across the entire region (e.g., continental United States). Wide area services usually broadcast corrections from GEO satellites, and for example use the GPS signal (special space-based augmentation system (SBAS) format and source code. Since the U.S. Wide Area Augmentation System (WAAS) operates on GPS/L1, virtually every commercial civil GNSS receiver today can use WAAS corrections.
- Local area services use one reference station and provide corrections based on it. The accuracy is greatest near the reference station and degrades as one gets further away. Coverage extends from a few miles to some 200 miles from the reference station. Local area services usually broadcast from a transmitter at the reference station (e.g., SC-104 uses marine radio beacon frequencies approximately 300 kHz.

DGNSS can be as simple as a small ground station outfitted with a GPS receiver, at a geographic location that is precisely determined by prior surveying. The timing error of each satellite's contribution to the error between the surveyed and the GPS position is transmitted by the ground station to a DGNSS receiver over a different frequency. The differential station can also be mobile on the Earth's surface, airborne, or in space, but is not as accurate as the ground station that is pre-surveyed. The position of the ground or airborne station can also be transmitted at a frequency different from that used by GPS or at a GPS frequency. The timing error signal can improve positioning accuracy significantly from the current GNSS positioning accuracy of 10 meters to less than 1 meter.

A tutorial explanation of differential GNSS is at: http://www.trimble.com/gps/advanced2.html

The new U.S. Space-based positioning, navigation, and timing policy was authorized by President Bush on 8 December 2004. http://www.navcen.uscg.gov/cgsic/geninfo/FactSheet.pdf

DSTL DATA SHEET 16.3-3. GNSS ANTI-JAM COMPONENTS AND SYSTEMS

Technology Parameter(s)	In the next 5 to 10 years, the following will have the potential to significantly enhance or degrade U.S. military capabilities: *A. Adaptive Antenna Systems should be:* 1. Fully integrated multiple-element antenna array and antenna electronics (e.g., signal processing unit). 2. Have a nearly uniform hemispherical gain pattern when there is no external RF interference. Gain better than –3.5 dB (over a 160-deg solid angle). 3. Creates, in the presence of multiple RF sources, a null in the direction of unintentional or intentional interference signals. – Null depth > 25 dB. – Adaptive speed < 10 microseconds. 4. Creates, in the presence of multiple RF sources, an antenna gain in the direction desired GPS satellite: gain > 10 dB. 5. Overall processing gain: GPS receiver, antenna, and antenna electronics: > 61 dB total. 6. Less than 4 inches in diameter for a four-element array. *B. Adaptive Narrowband Filters should:* 1. Receive, condition, and convert GPS RF signal to digital IF signal. 2. Apply time, frequency, or amplitude-domain signal-processing techniques to remove interference signal that exists above thermal noise level. – Temporal (time) adaptive transversal filter performance 30 dB [narrow band (NB)]. – Spectral (frequency) digital excision filter performance 30 dB [continuous wave (CW)]. – Nonlinear amplitude domain processor performance 20 dB (CW).
Critical Materials	Materials to implement low-observable requirements may or may not be used.
Unique Test, Production, Inspection Equipment	GPS JPO must verify test suppression capability and test scenarios. GPS simulators.
Unique Software	Any software that includes the following: 1. Features validated null-steering, beam-steering, or beam-pointing algorithms. 2. Features validated space-time adaptive processor (STAP) algorithm. 3. Features validated space-frequency adaptive processor (SFAP) algorithms.
Major Commercial Applications	Ground-vehicle navigation, aircraft and space navigation, underwater-vehicle navigation, mining, and farming and telecommunications.

Affordability	Increased commercialization will significantly reduce cost.

BACKGROUND

Various adaptive interference suppression technologies are being researched to overcome the susceptibility to GPS signal jamming, both intentional and unintentional. There are currently three techniques being researched for improving antijam for GPS receivers: (1) use of ultra tight GPS/inertial coupling as discussed in Data Sheet 16.1-2, (2) use of improvements of processing gain and (3) use of antenna enhancement techniques. Both the later techniques are discussed in this data sheet. The use of an autonomous, low-power clock within the GPS receiver or INS, that can minimize GPS jamming, loss of satellite signal and reacquisition, is discussed in Section 16.5.

Anti-jam GPS components and systems, such as an adaptive antenna systems and adaptive narrowband filters, will optimize antenna coverage patterns to specific signal and interference environments. This will produce an antenna pattern with nulls in the direction of the jamming signal very quickly.

DSTL DATA SHEET 16.3-4. GNSS INDOOR NAVIGATION SYSTEMS

Technology Parameter(s)	In the next 5 to 10 years, the following will have the potential to significantly enhance or degrade U.S. military capabilities: 1. Ability to locate and track a cooperative individual's position inside a building to within 5 centimeters. 2. Ability to navigate inside a building to within 5 centimeters.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Algorithms and source codes that reduce signal detectability, including antenna cross-correlation algorithms and verified data.
Major Commercial Applications	Navigation devices for the blind, indoor navigation, medical surgical instruments, and robotics.
Affordability Issues	None identified.

BACKGROUND

The Global Positioning System (GPS) is the primary GNSS navigation technology used for both military and commercial applications. However, GPS does not work inside buildings or infrastructures because of the system's characteristics. This is a particular concern for the military in an urban environment where seamless navigation in both outdoor and indoor environments is critical. The requirement of the Federal Communication Commission's Enhanced 911 rule to require cell phones have positioning capability has recently spurred commercial investments for solutions of this limitation. There are several technologies being researched. This data sheet addresses the following indoor technologies: (1) use of GPS-like pseudolites, (2) an enhanced A-GPS performance enough to get the extra processing gain required to acquire GPS signal indoors, (3) re-transmitting GPS signals using RF or Ultra-Wideband (UWB) antennas, (4) utilizing timing information embedded in existing RF, UHF, and VHF systems (e.g., cellular phone networks), and (5) other technologies such as ultrasound or lasers.

DSTL DATA SHEET 16.3-5. GNSS INTERFERRENCE AND JAMMING LOCATION SYSTEMS

Technology Parameter(s)	In the next 5 to 10 years, the following will have the potential to significantly enhance or degrade U.S. military capabilities: *A. Direction-finding ability to:* 1. Detect and locate GNSS jamming signal instantaneously. 2. Having a processing rate of more than 10,000 direction-finding results per second and per frequency channel. 3. Having a relative bearing accuracy of better than 0.1 deg line of signal (LOS) from transmitter. *B. Jamming ability to:* 1. Jam hostile forces from using GNSS signals.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Test, calibration, or alignment equipment specially designed for direction-finding equipment at the above technology parameters.
Unique Software	Source code for the development of this equipment.
Major Commercial Applications	General aviation and police (vehicle and hostage tracking).
Affordability Issues	Not an issue.

BACKGROUND

GNSS interference and jamming location systems uses the same principles as direction finding (DF) equipment but specially focused on the bearing and location of hostile GNSS jammers. Direction-finding (DF) equipment determines the direction of a transmitter by means of its emission. DF equipment uses the reception of radio waves for the purpose of determining the bearing to a station or object.

DSTL DATA SHEET 16.3-6. ENHANCED LORAN (E-LORAN) SYSTEMS FOR NAVIGATION

Technology Parameter(s)	In the next 5 to 10 years, the following will have the potential to significantly enhance or degrade U.S. military capabilities: 1. Ability to be used effectively in military urban, mountainous, naval and other operations using mobile eLORAN transmitters under control and management of U.S. forces. 2. Ability to be integrated into the GPS receiver architecture with minimal increase in cost, size and weight of the receiver. 3. Ability to be designed for minimal integration costs into weapon systems.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Testing of seamless operation in advent of GPS signal loss. Integrated architecture of a combined GPS/LORAN receiver.
Unique Software	Integration of GPS/LORAN signals for enhanced performance in urban, mountainous, naval, and other operations. Ensuring seamless operation in advent of GPS signal loss.
Major Commercial Applications	Navigation for commercial aviation and commercial vessels.
Affordability Issues	Integration of eLORAN receivers and antennas into weapon systems could be extremely costly.

BACKGROUND

Enhanced long-range navigation (E-LORAN) is a system that incorporates the latest receiver, antenna, and transmission system technology to enable LORAN-C[22] to serve as a back-up and complement to Global Navigation Satellite Systems (GNSS) for navigation and timing. This latest technology provides substantially enhanced performance beyond what was possible with LORAN-C. For example, it is now possible to obtain absolute accuracies of 8–20 meters using E-LORAN for harbor entrance and approach and other application in a local area. Similarly, E-LORAN can function as an independent, highly accurate source of frequency and universal time coordinated (UTC).[23] For more information on this timing capability refer to Section 16.5.

The following are some of the improvements of eLORAN over previous LORAN-C systems:

- One of the major enhancements to LORAN-C was to synchronize all LORAN stations, master and secondary, to a single, absolute time reference (i.e., a “chainless” system with a time-of-transmission architecture similar to GPS) and allow receivers to use signals from all the stations it can receive at any given time to calculate an even more accurate position. Today’s all-in-view LORAN receivers can monitor dozens of stations simultaneously from several LORAN chains. Bringing more stations into the navigational net enhances accuracy, as the receivers automatically select an optimal combination of stations to obtain the best positioning solution.

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22 LORAN-C is a 2D low-frequency terrestrially-based, radionavigation system where a number of stations broadcast high-power (250–1500 kW) pulses in the 100 kHz band. The accuracy of LORAN-C (100–300 meters) depends on the geometry of the stations and the user, and also on the accuracy of correction factors available in the area of interest.

23 http://www.locusinc.com/pdf/LORAN%20BrochureUFFC2004WithLogo.pdf

- Powerful correlation techniques enable receivers to pick out signals as low as 25 dB below what was previously possible, providing ranges up to approximately 190 miles (305 km) greater than those of previous-generation systems.
- Today's receivers mitigate much of the inaccuracy caused by the effects of terrain on the LORAN signals. Modern digital receivers also deliver advanced signal processing, adaptive digital filtering, and high processing speeds.
- High system redundancy allows for autonomous integrity checking.
- LORAN signals can now be accurately resolved to 1 nanosecond in time, 100 times better than older-generation receivers could achieve. This is crucial both because positions are derived from the signals' times of arrival (TOA) and because LORAN not only backs up the positioning functions of GNSS, but also offers an alternative time and frequency source.
- Addition of a 9th pulse to carry differential LORAN, station identification, UTC, leap second, integrity and other information on LORAN.

Differential eLORAN works the same way as Differential GPS (Data Sheet 16.3-2) except that with LORAN you must account for the significant signal delay that results from the land-path propagation. Each waterway has to be surveyed ahead of time and Additional Secondary Factors (ASFs) collected and made available to be stored in the user receiver. A shore-side monitor is set up in each waterway that calculates temporal corrections and sends them to a LORAN station in real time. The LORAN station modulates this information and broadcasts the corrections, embedded on a new ninth pulse that is used solely for data communication, to the user. The user receiver then applies the ASFs and the monitor corrections to the LORAN fix to improve accuracy to within 20 meters.

In Europe, eLORAN has been implemented in a slightly different way than in the United States, although European LORAN still uses a time-of-transmission architecture. Here, use of eLORAN as a regional GNSS augmentation system is called Eurofix.[24] See Figure 16.3-1. The principal components of Eurofix are the satellite-based radionavigation systems GPS and/or GLONASS (or the future Galileo) and the terrestrial radionavigation system LORAN-C (and/or its Russian counterpart Chayka). The LORAN-C signals are used as carriers for a multi-channel long-range (up to 1500 km) communication system to broadcast differential corrections and other messages. Thereby, the normal navigation mode of LORAN-C is preserved. This integration of ground-based and satellite-based navigation systems aims at the exploitation of the advantages of both components and, thus, improves navigation performance. LORAN signals are pulse position modulated to provide DGPS, DGLONASS, navigation integrity messages and short message services and the system has additional capacity for future applications.

Figure 16.3-1. Basic principle of Eurofix that provides corrected DGNSS signals to Northwest Europe. (Source: http://www.geof.hr/~dmedak/dub2000/eurofix.htm.)

[24] EUROFIX uses LORAN-C to broadcast DGPS and integrity messages. The normal navigation operational mode of LORAN-C is unaffected. Therefore the Eurofix user has DGPS information for his GPS system plus a completely interdependent navigation system. If either GPS or LORAN-C fails, the other system still provides position information.

DSTL DATA SHEET 16.3-7. DOPPLER (RADAR OR SONAR) NAVIGATION SYSTEMS

Technology Parameter(s)	In the next 5 to 10 years, the following will have the potential to significantly enhance or degrade U.S. military capabilities: *A. For both airborne and underwater applications:* 1. Low Probability of Intercept (LPI) using power management or phase-shift-key modulation techniques that allow signals to reach ground from 5,000 meters altitude or sea bed of depths greater than 1,000 meters. 2. Low Probability of Detection (LPD) using any technique that reduces signal detectability, including antenna beam steering technology. *B. For airborne applications:* 1. Velocity error of less (better) than 0.05 percent of distance traveled. *C. For underwater applications:* 1. Velocity error of less (better) than 0.1 percent of distance traveled. 2. Combined with a heading sensor of 0.1 degree will provide an underwater positioning accuracy of less (better) than 40 meters for a range of 10,000 meters.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Algorithms and source codes that reduce signal detectability, including antenna cross-correlation algorithms and verified data.
Major Commercial Applications	None identified for LPI/LPD technology, but basic Doppler navigation systems have wide applications in commercial aviation, space, land, and sea vehicles, including weather tracking.
Affordability Issues	Military-unique LPI software requirement may drive up cost, unless hardware maximizes commercial technology.

BACKGROUND

A Doppler (radar or sonar[25]) sensor measures the velocity changes of a vehicle over the surface (land or surface of water) or seabed. Studies have shown that accurate and precise attitude sensing is essential for accurate Doppler navigation. Therefore an integrated Doppler (radar or sonar) navigation system integrates measured velocity (Doppler sensor) with a heading sensor which is used to resolve the vehicle's position into geographic coordinates. The following basic Doppler navigation error model shows the effect of heading error.

$$\text{Total error } (1\sigma) = \sqrt{\varepsilon_P^2 + (D\sin\phi_0)^2 + (D\sin\phi_{DI})^2 + (D\cdot\delta V_0)^2 + (D\cdot\delta V_A)^2}$$

Where:

ε_P = initial vehicle position error

ϕ_0 = initial heading error

ϕ_{DI} = sensor heading misalignment

δV = along-track velocity error (% of distanced traveled)

δV_0 = cross-track velocity error (% of distanced traveled)

D = Distance traveled

25 http://www.its.bldrdoc.gov/fs-1037/dir-034/_4963.htm

The values for these terms are combined to give a root-sum-square estimate (1σ) of vehicle position error as a function of distance traveled (D). All of these error contributions are independent of vehicle speed and higher order terms such as heading drift rate error are not included. It should also be stressed that this is a worst case scenario that assumes the vehicle is on a constant heading throughout the mission.[26]

The Doppler velocity sensor determines velocity and drift angle by measuring the Doppler frequency shift (Doppler Effect) from narrow radar or sonar (**so**und **n**avigation **a**nd **r**anging) beams transmitted at oblique angles from the vehicle toward the ground or seabed. For underwater navigation this technology provides changes in the estimate of a vehicle's position without the need for external acoustic devices.

For acoustic positioning systems (APS) that use transducers and transponders to determine a vehicle's position refer to Data Sheet 16.3-7. For additional information on the Doppler effect, see http://astrosun.tn.cornell.edu/courses/astro201/doppler.htm. Refer to Section 13, Marine Systems.

26 http://www.ise.bc.ca/WADEnavandpos.html

DSTL DATA SHEET 16.3-8. UNDERWATER ACOUSTIC BEACON NAVIGATION SYSTEMS

Technology Parameter(s)	In the next 5 to 10 years, the following will have the potential to significantly enhance U.S. military capabilities for underwater acoustic navigation: 1. Acoustic positioning systems for surface or underwater vessels having position error less than 10 m (CEP) at ranges greater than 1,000 m. 2. Availability of underwater APS transducers over 10% of the world's oceans. In the next 10 to 20 years: 1. Availability of underwater APS transducers with position accuracy to within 10 meters over 25% of the world's oceans.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Algorithms and source codes that reduce signal detectability, including antenna cross-correlation algorithms and verified data.
Major Commercial Applications	Underwater search and rescue, pier and harbor docking.
Affordability Issues	None identified.

BACKGROUND

Passive underwater acoustic positioning systems provide a surface ship or submarine (manned or unmanned) with a relative position achievable with transducers on the vessel (acoustic listening devices) and a network of acoustic transponders (transmitters) external to the vessel that provides coordinates of an acoustic grid. This technology can provide an underwater passive acoustic navigation system similar to GPS, by pre-surveying the geodetic location of each transponder and either being deployed (1) as an active GPS buoy on the surface of water and pinging signals underwater or (2) anchored to the seabed.

The fundamental concept of passive acoustics navigation is basically the same as satellite navigation. Both are based in Cartesian navigation. In place of satellites, transducers or pingers transmit acoustic signals at different frequencies. These transponders are placed in a known array pattern and can either (1) be continuously active or (2) remain passive until queried by a vessel. The latter requires the vessel to actively transmit. Most commercial surface vessels currently use this type. The receiver is a microphone interrogator that transmits an acoustic signal and measures the time to receive a reply. The time difference is a function of distance from the transponder. More than one transponder is required to establish a position fix. Better performance can be obtained by increasing the number of transponders. There are two common types of acoustic navigation: (1) short or ultra-short baseline and (2) long-baseline.

For additional information go to this website: http://ocw.mit.edu/NR/rdonlyres/Ocean-Engineering/13-49Maneuvering-and-Control-of-Surface-and-Underwater-VehiclesFall2000/3D5A4E76-63E6-49E0-93E9-1CA5E4731CC1/0/chap22.pdf

DSTL DATA SHEET 16.3-9. VISION NAVIGATION SYSTEMS

Technology Parameter(s)	In the next 5 to 10 years, the following will have the potential to significantly enhance U.S. military capabilities: 1. An all weather, day/night vision navigation system capable of navigating in air, on surface or underwater with position error less than 1 m (CEP) independent of vehicle speed, and distance of human control station.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Algorithms and source codes that reduce signal detectability, including antenna cross-correlation algorithms and verified data.
Major Commercial Applications	Medical surgical instruments and robotics. Inspection of piers and dams. Monitoring of underwater structures. Search for the drowned personnel or critical assets. Safety monitoring for underwater pipes and cables.
Affordability Issues	None identified.

BACKGROUND

This technology includes the use of cameras and RF links for navigation of robots or unmanned vehicles. See Figure 16.3-2. Positioning is based on optic technology (i.e., cameras, TV, infrared), and relayed via a communication link (i.e., RF, UWB, internet) to a remote sight to navigate the vehicle. No prior imagery of a target (or reference point) is required. For an autonomous vision navigation system refer to Section 16.7, and for an autonomous imaging system using a pre-stored terrain database refer to Data Sheet 16.3-13.

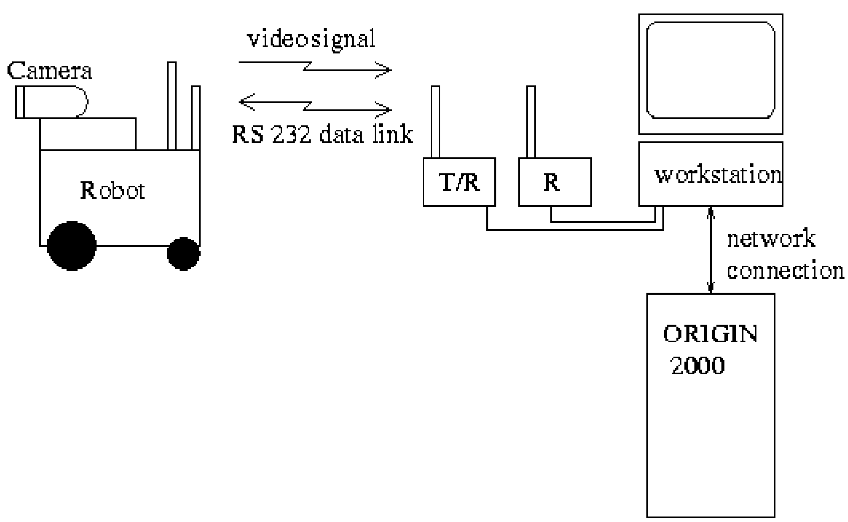

Figure16.3-2. Vision based navigation system based on real-time imaging and communication link. (Source: York University[27])

27 http://www-users.cs.york.ac.uk/~nep/research/vn.htm

DSTL DATA SHEET 16.3-10. HYBRID[28] NAVIGATION SYSTEMS (OTHER THAN INERTIAL NAVIGATION SYSTEMS)

Technology Parameter(s)	In the next 5 to 10 years, military navigation systems will most likely be a combination of GPS + Galileo + Telecommunications (JTIDS/EPLRS) + Doppler Sonar or DBRN and having the following performance: 1. Position accuracy less than 1 meter. 2. Velocity accuracy less than 0.01 meters per second. 3. Pointing or heading accuracy of less than 10 arc second. 4. Attitude accuracy of less than 30 arc second. 5. Jam resistant. *Note: For hybrid inertial navigation systems/GNSS refer to Section 16.1.*
Critical Materials	Tamper-resistant thermal-spray technology to protect components containing sensitive U.S. cryptographic logic.
Unique Test, Production, Inspection Equipment	• Components require specially designed test, calibration, or alignment equipment. • GNSS receivers requiring special simulator testing systems. • Specially designed test, calibration, or alignment equipment. • Antispoofing and signal simulators with less (better) than 28 ns measurement capability; ECCM or interference resistance receivers.
Unique Software	Source code, algorithms, and verified data needed to meet above parameters with any of the following navigation data: 1. LORAN, Doppler (radar, laser, or sonar), or DBRN (bathymetric, stellar, gravity, and magnetic databases, or 3–D digital-terrain maps and other geomapping data), JTIDS, or EPLRS.
Major Commercial Applications	Ground-vehicle navigation, aircraft and space navigation, underwater-vehicle navigation, mining, and farming.
Affordability Issues	Accuracy and autonomy are the key cost drivers.

BACKGROUND

Using data-fusion computing techniques, hybrid radio-navigation systems, such as GNSS (GPS + GLONASS + Galileo), or any combination of LORAN, Doppler (radar, laser or sonar), Data Based Referenced Navigation (DBRN) Systems (e.g., terrain, bathymetric, stellar, magnetic, or gravity sensing from a priori databases) and/or communications systems (i.e., JTIDS[29] or EPLRS[30]) can provide increased positioning accuracy. In addition, hybrid radio navigation also provides a "flywheel" effect for continuous, accurate navigation, even when any one of these other navigation signals is lost. This is especially critical in a high jamming environment. For hybrid GNSS/INS refer to Data Sheet 16.1-2.

28 The term hybrid means the different technologies are either "integrated" or "embedded."

29 JTIDS Description: http://www.fas.org/man/dod-101/sys/land/jtids.htm

30 EPLRS Description: http://www.monmouth.army.mil/peoc3s/trcs/EPLRSDescr.htm

DSTL DATA SHEET 16.3-11. LPI/LPD RADAR ALTIMETERS AND FATHOMETERS

Technology Parameter(s)	In the next 5 to 10 years, any radar altimeter or fathometer (also called a depth finder with the following characteristics will have the potential to significantly enhance or degrade U.S. military capabilities 1. Non-detectable in radar frequency range. 2. Integrated with LPI limited-range, forward-looking sensor and terrain databases for better situational awareness in low-altitude terrain avoidance. 3. Altitude accuracy: ± 1 foot at 0 to 5,000 ft. 4. ± 25 feet at 5,000 to 60,000 ft.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Algorithms and source codes that reduce signal detectability, including antenna cross-correlation algorithms and verified data.
Major Commercial Applications	None identified for LPI/LPD technology, but basic radar altimeter and fathometer systems have wide applications in commercial aviation, space, land, and marine vehicles.
Affordability Issues	Military-unique LPI software requirement may drive up cost, unless hardware maximizes commercial technology.

BACKGROUND

Radar altimeters provide height-above-terrain, while fathometers provide distance above ocean seabed. The use of low probability of intercept (LPI) or low probability of detection (LPD) techniques reduces the emitting power of these devices as shown in Figure 16.3-3.

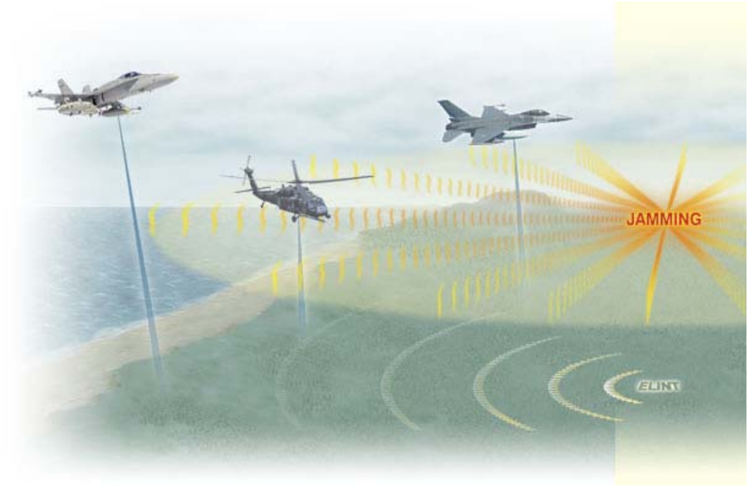

Figure 16.3-3. Concept: Use of LPI Altimeter in a High ECCM Environment (Source: BAE Systems)

DSTL DATA SHEET 16.3-12. STELLAR DATA-BASED REFERENCED NAVIGATION (DBRN) SYSTEMS AND DATA SOURCES

Technology Parameter(s)	In the next 5 to 10 years, the following will have the potential to significantly enhance or degrade U.S. military capabilities: 1. Automated celestial navigation systems, with day/night observing capability, will be used for marine and air navigation. Position accuracy of 10 m SEP or better will be attained, and the systems will be able to determine platform attitude and absolute azimuth to several arcseconds (an arcsecond is1/3600 of a degree). 2. Newly developed star trackers and their associated high precision star catalogs will be used for satellite navigation, orientation, and calibration at several times current accuracies.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Star trackers; Specially designed optical systems and solid-state focal plane arrays enabling daytime observations of celestial bodies at or near the Earth's surface.
Unique Software	Star catalogs and software to access the catalogs; high-accuracy sight reduction algorithms; algorithms for enhancing star contrast and SNR in sky images, star pattern recognition, and integration with inertial navigation systems (under development)
Major Commercial Applications	Marine, aircraft, and space navigation and orientation.
Affordability Issues	Cost of the star trackers and associated software; development of very high accuracy star catalogs (single-milliarcsecond regime), which will require new, dedicated Earth-bound telescopes and/or dedicated space missions.

BACKGROUND

Stellar[31] Data-Based Referenced Navigation (DBRN[32]) systems use *a priori* star catalogs to provide a means of obtaining position and platform attitude (including absolute azimuth), and course and speed when the platform is moving. Using celestial as reference points is perhaps the only way to obtain a direct, precise measurement of azimuth.

There are two distinct categories of navigation; each uses a different "database" as follows:

1. "Traditional" celestial[33] navigation: This is typically practiced at or near the Earth's surface (e.g. a ship, some aircraft). The instrument is a sextant. The "database" is an almanac (e.g., The Nautical Almanac or The Air Almanac). The astronomical data in the almanacs—positions of the Sun, Moon, navigational planets, and bright stars—are precise to ~0.1–1 arcminute (an arcminute is 1/60th of a degree). Many countries publish their own almanacs, and the joint US/UK navigational almanacs are available worldwide for public sale. *This is not the subject of this Data Sheet.*

2. Stellar navigation: This is typically practiced at high aircraft altitudes and from space (e.g., some military aircraft, the Space Shuttle, the International Space Station, missiles and satellites). The sensing instrument is typically an automated star tracker. The "database" is a star catalog (see

31 Stellar navigation only uses the positions of the stars.

32 The Wassenaar Arrangement's definition of 'Data-Based Referenced Navigation' (DBRN) Systems is "systems, which use various sources of previously measured geo-mapping data integrated to provide accurate navigation information under dynamic conditions. Data sources include bathymetric maps, stellar maps, gravity maps, magnetic maps or 3-D digital terrain maps."

33 Celestial navigation uses the position of the sun, moon and stars.

http://ad.usno.navy.mil/star/star_cats_rec.shtml) containing the positions, motions, and magnitudes of a selected set of stars, tuned to the response of the star tracker's detector. A modern, non-military star tracker can determine orientation of a platform to ~0.7 to 2 arcsecond. Most military applications integrate stellar navigation with an inertial navigation system (for determination of the local vertical) and GNSS (for precise time reference). One of the primary reasons for Stellar/INS integration is that the star tracker provides a position and attitude fix that constrains INS drift, while the INS provides a local vertical reference, ands serves as a "flywheel" during periods when observations cannot be obtained. Automated celestial navigation systems also are under development for use at or near the Earth's surface.

There are at least four other basic types of DBRN systems and data sources: terrain (altitude and imaging), bathymetric (depth and imaging), magnetic and gravity that are discussed in Data Sheets 16.3.13 through 16.3-16 respectively. For all cases of these DBRN systems, there is a computation and correlation process with a pre-surveyed database or a map used as the reference for comparing sensor information to determine position. Accurate time is also required for computation and data resolution.

Figure 16.3-4 describes a conceptual stellar-DBRN system where the sensor can be a star tracker. A synergistic or hybrid Stella-DBRN systems describes a system that integrates a stellar DBRN system with another DBRN system (e.g., terrain DBRN or magnetic DBRN) to provide a more accurate method of obtaining position when the platform is on the earth's surface or in space.

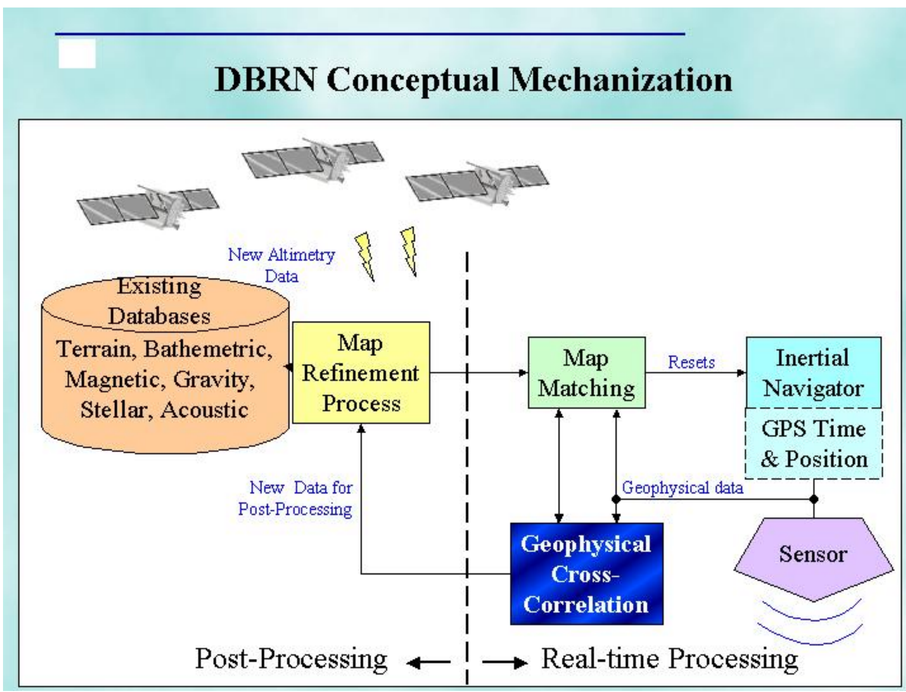

Figure 16.3-4. Conceptual Description of a DBRN System (Source: ARL, Penn State)

DSTL DATA SHEET 16.3-13. TERRAIN DATA-BASED REFERENCED NAVIGATION (DBRN) SYSTEMS AND DATA SOURCES

Technology Parameter(s)	In the next 5 to 10 years, the following will have the potential to significantly enhance or degrade U.S. military capabilities: 1. Terrain (Altitude or Imaging) Data-Based Referenced Navigation System (DBRN) will provide surface or airborne positioning accuracy of less (better) than 30 meters CEP worldwide where terrain correlation is viable. 2. Within 20 years, terrain DBRN will provide surface or airborne positioning accuracy of less (better) than 10 meters CEP worldwide where terrain correlation is viable.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Unique computer test models for optimization of database manipulation and extraction.
Unique Software	Algorithms for image correlation and pattern recognition. Integration and data-analysis algorithms and verified data. • Source code, algorithms, and verified data needed to exceed above parameter with any of the following navigation data: acoustic positioning systems, or stellar, magnetic, and gravity mapping data.
Major Commercial Applications	Ground-vehicle and aircraft navigation, underwater-vehicle navigation, mining, farming, and surveying.
Affordability Issues	Mapping data source, worldwide coverage, and accuracy are the key cost drivers.

BACKGROUND

Terrain[34] Data-Based Referenced Navigation (DBRN) systems[35] that use a priori data sources or maps provide a means of obtaining position and direction when the platform is moving. There are two main types of Terrain DBRN: altitude matching or image matching. For all cases of DBRN systems, there is a computation and correlation process with a star catalog, a pre-surveyed database or a map used as the reference for comparing sensor information profiles to determine position. Accurate time is required for computation and data resolution. Figure 16.3-5 describes a conceptual DBRN system where the sensor for a Terrain DBRN can be a radar altimeter, barometric altimeter or for imaging an optical sensor: infrared or camera.

Synergistic or Hybrid Terrain DBRN systems combine other a priori data sources or maps and other navigation systems (i.e., INS or GNSS) to provide a covert or low probability of detection means of obtaining position and direction when the platform is on the earth's surface or in the air above the surface.

[34] Terrain is synonymous with Topography.

[35] The Wassenaar Arrangement's definition of 'Data-Based Referenced Navigation' (DBRN) Systems is "systems, which use various sources of previously measured geo-mapping data integrated to provide accurate navigation information under dynamic conditions. Data sources include bathymetric maps, stellar maps, gravity maps, magnetic maps or 3-D digital terrain maps."

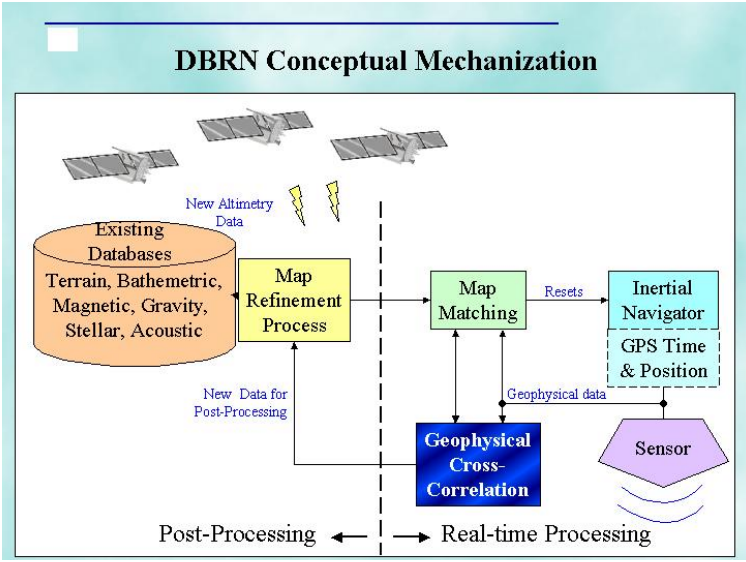

Figure 16.3-5. Conceptual Description of DBRN Systems (Source: ARL, Penn State)

Terrain DBRN Systems use a pre-stored database of terrain from a commercial or government agency such as the National Geospatial-Intelligence Agency (NGA) that basically provides the *terrain profile* (altitude, Latitude & Longitude). Terrain DBRN only applies to navigating relative to the surface or air above the surface. There are three different categories of Terrain DBRN Systems.

1. *Terrain-Altitude DBRN Systems for airborne vehicles* use a barometric altimeter as a mean sea level reference and a RADAR altimeter, RADAR or a Laser RADAR (LiDAR) to determine terrain elevation. This system compares the “along track” terrain elevation or ground swath profile data with a pre-stored data base, using low probability of intercept techniques to reduce delectability of the radar signal.

2. *Terrain-Altitude DBRN Systems for land vehicles* use a barometric altimeter to covertly determine terrain elevation. This system compares the “along track” terrain elevation with the pre-stored database.

3. *Terrain-Imaging DBRN System for both airborne and land vehicles* correlates cross track images with terrain profile data. Imaging DBRN Systems can use optical, infrared and ultraviolet technology to covertly obtain position.

Figure 16.3-6 shows an example of an Altitude DBRN for an air vehicle. Additional data such as digital maps with railroad track geometry enable positioning accuracy to within 10 feet (3 sigma) along the track. Areas where the terrain changes are where these type systems work best.

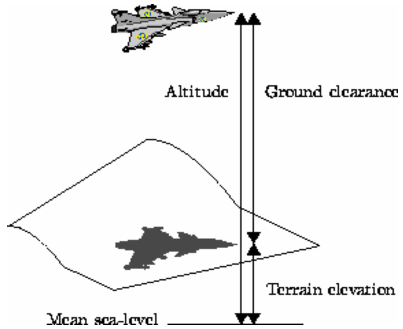

Figure 16.3-6. Altitude DBRN for air vehicle[36]

[36] http://www.control.isy.liu.se/research/sp/sp/node1.html

The use of imaging sensors and digital terrain maps for determining a position is relatively new. Positioning is based on photogrammetry and video imagery technology. Prior imagery of a target (or reference point) is required to be cataloged and stored in a computer. Vision sensors combined with a navigation algorithm based on perspective estimation techniques determines the relative position and orientation of a vehicle with respect to the target. A related technology includes use of passive millimeter wave technology to generate images for passive signatures. See Section 10 Information Technology.

An Imaging DBRN System for an airborne or ground vehicle is pictorially represented in Figure 16.3-7. Geospatial Information and Services (GI&S) is the new term for Mapping, Charting and Geodesy (MC&G). GI&S incorporate the processes that collect, manage, extract, store, disseminate, and exploit geographic information and imagery. A GIS is essentially a computer program.

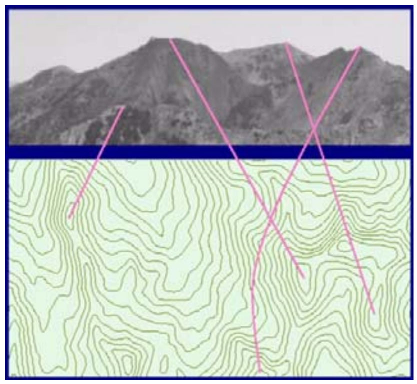

Figure 16.3-7. Terrain Imaging DBRN system. Source: University of Utah[37]

[37] http://www.cs.utah.edu/vision/navigation.html

DSTL DATA SHEET 16.3-14. BATHYMETRIC DATA-BASED REFERENCED NAVIGATION (DBRN) SYSTEMS AND DATA SOURCES

Technology Parameter(s)	In the next 5 to 10 years, the following will have the potential to significantly enhance or degrade U.S. military capabilities: 1. Bathymetric Data-Based Referenced Navigation System (DBRN) providing an underwater positioning accuracy of less (better) than 150 m CEP.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Unique computer test models for optimization of database manipulation and extraction.
Unique Software	Algorithms for image correlation and pattern recognition. Integration and data-analysis algorithms and verified data. • Source code, algorithms, and verified data needed to exceed above parameter with any of the following navigation data: acoustic positioning systems, or magnetic, and gravity mapping data.
Major Commercial Applications	Ship navigation, underwater-vehicle navigation, mining, farming, and surveying.
Affordability Issues	Mapping data source, worldwide coverage, and accuracy are the key cost drivers.

BACKGROUND

Bathymetric Data-Based Referenced Navigation (DBRN) Systems[38] when combined with a priori data sources or maps provide a means of obtaining position and direction when the platform is moving. For all cases of DBRN systems, there is a computation and correlation process with a star catalog, a pre-surveyed database or a map used as the reference for comparing sensor information profiles to determine position. Accurate time is required for computation and data resolution. Figure 16.3-8 describes a conceptual DBRN system where the sensor for a Bathymetric DBRN can be a sonar radar or depth finder. Bathymetric imaging uses acoustic instruments such as sidescan sonar or "backscatter" returns from a swath bathymetry. This imagery is the acoustic equivalent of a sideways-looking airborne radar or synthetic aperture radar (SAR).

Synergistic or Hybrid Bathymetric-DBRN systems combine other a priori data sources or maps and other navigation systems (i.e., INS or GNSS (on-surface)) to provide a covert or low probability of detection means of obtaining position and direction when the platform is on the water surface or underwater.

Bathymetric data sources only apply to underwater. The DBRN system that uses this data source must be either on the water's surface or underwater.

[38] The Wassenaar Arrangement's definition of 'Data-Based Referenced Navigation' (DBRN) Systems is "systems, which use various sources of previously measured geo-mapping data integrated to provide accurate navigation information under dynamic conditions. Data sources include bathymetric maps, stellar maps, gravity maps, magnetic maps or 3-D digital terrain maps."

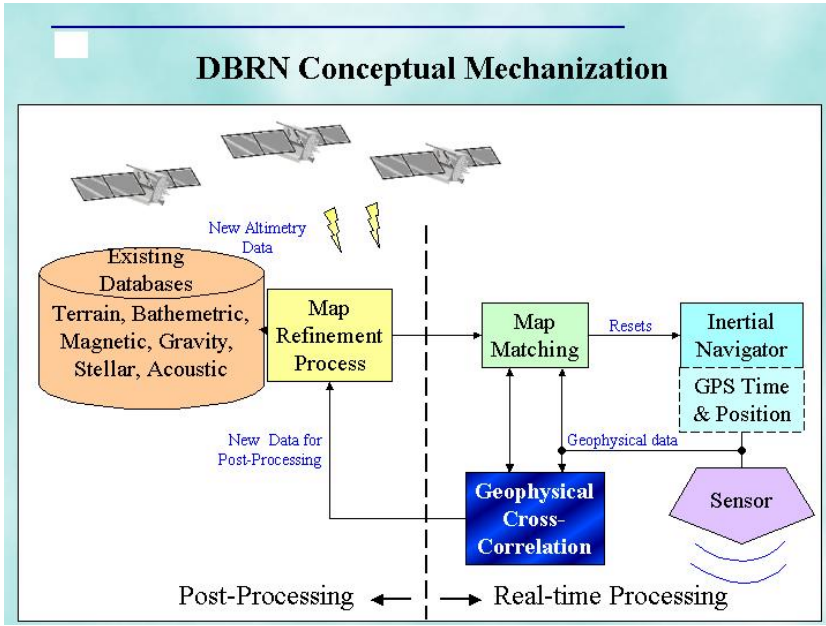

Figure 16.3-8. Conceptual Description of DBRN Systems (Source: ARL, PennState)

These systems use a pre-stored database of bathymetric data from a commercial or government agency such as the Naval Oceanographic Office (NAVOCEANO) that basically provides the seabed profile (depth, Latitude & Longitude). The two different types of Bathymetric DBRN Systems are described below.

1. *Bathymetric-Acoustic (Topography) DBRN System* for sea surface or underwater vehicles measures *"along track"* profile using an acoustic sensor (active or passive), LIDAR (for shallow, clear water only) or Fathometer and a pressure sensor for underwater vehicles to determine overall depth to the seabed. This system then compares the along track position information (swath (multiple returns per ping) or profile data) from the pre-stored database to determine positioning information.

2. *Bathymetric-Acoustic (Imaging) DBRN System* for both sea surface and underwater vehicles correlates pre-stored *"cross track"* sea floor swath data with image data. This system is similar to the bathymetric topography system described above in that it images the sea bed in "scan"-type lines. Unlike a camera that obtains an image of an area, the acoustic sensor sends out one ping to get a single cross track scan of the seabed. The sensor needs to be moving over the seabed and the composite image can then be used. However these sensors do radiate. Imaging DBRN Systems are done acoustically with instruments such as sidescan sonar or "backscatter" returns from a swath bathymetry. Backscatter is derived from a hull mounted array, such as a multi-beam echo sounder. http://www.km.kongsberg.com/ks/web/NOKBG0397.nsf/AllWeb/40CAF251EE1E4587C1256DC00038D0D2/$file/Paper2-4_Testing_Multibeam-IHO.pdf?OpenElement or sidescan sonar http://www.l-3klein.com/ssdescription/ssdescription.html

Both systems use the same sea floor profile data base. A Bathymetric DBRN system on a vessel (surface or underwater) uses a gyroscopic system to maintain the system's attitude and true vertical as a reference in a correlation process that results in a statistically insignificant position on the seabed. Only with continuous movement of the vessel over/along seabed differences (bathymetric contours or image) and measurement of the bathymetric contours or image of the seabed and correlation to the pre-stored sea floor bathymetry or image database can the vessel's position be computed. Continuous determination of position over time will provide direction from which, with time, will provide other navigation information, such as velocity and distance traveled. Sonar systems can be designed with "less detectable noise," but must necessarily broadcast a signal sufficiently strong to generate a sea floor echo. This type system works best in areas where the sea floor profile changes. The accuracy of the position is directly related to the quality of the referenced database, the accuracy of the sensed profile and the correlation/computational (matching) errors.

Users of bathymetric data distinguish between 1) maps, which are generally artful to creative interpretations of limited data; 2) databases, which are digital representations of observations; and 3) grids, which are mathematical generalizations of a database.

Figure 16.3-9 pictorially represents an underwater bathymetric imaging database. This gives the illusion of apparent depth using color to indicate depth. The red end of the spectrum is for shallower depths; the rest of the colors go through to the dark blues as the seafloor gets deeper.

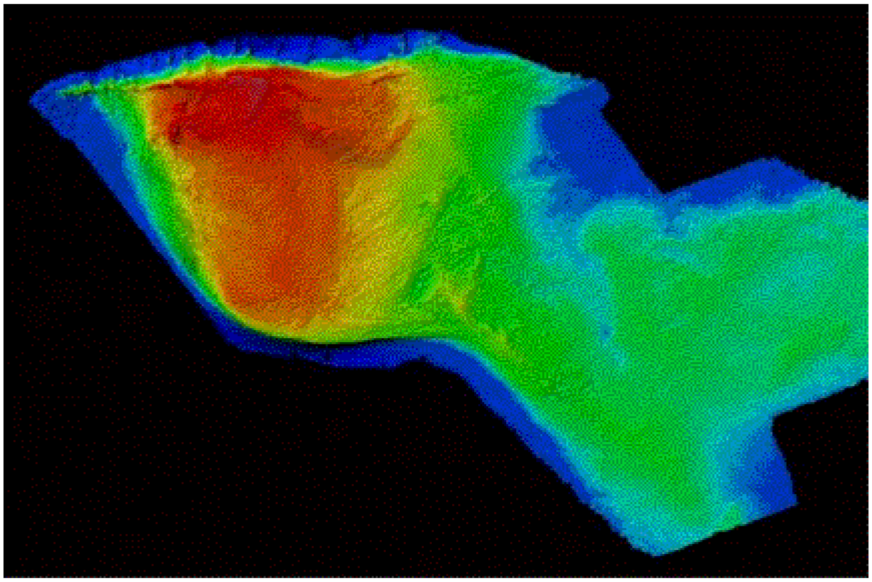

Figure 16.3-9. Image of seafloor generated from by the Canadian Hydrographic Service -Atlantic. It took sixty days and over 120 million soundings to map an area ~ 130 km by 70 km.[39]

[39] http://www.mar.dfo-mpo.gc.ca/science/review/1996/Lamplugh/Lamplugh_e.html

DSTL DATA SHEET 16.3-15. MAGNETIC AND ELECTRIC FIELD DATA-BASED REFERENCED NAVIGATION (DBRN) SYSTEMS AND DATA SOURCES

Technology Parameter(s)	In the next 5 to 10 years, the following will have the potential to significantly enhance or degrade U.S. military capabilities: 1. Magnetic Data-Based Referenced Navigation Systems (DBRN) having the following characteristics: a. Surface or airborne position accuracy of less (better) than 10 m CEP. b. Underwater position accuracy of less (better) than 250 m CEP. In the next 20 to 30 years, the following will have the potential to significantly enhance or degrade U.S. military capabilities: 1. Electric Field DBRN Systems having an under water position accuracy of 500 m CEP.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Unique computer test models for optimization of database manipulation and extraction.
Unique Software	Algorithms for image correlation and pattern recognition. Integration and data-analysis algorithms and verified data. • Source code, algorithms, and verified data needed to meet above parameters.
Major Commercial Applications	Ground-vehicle, ship and aircraft navigation, underwater-vehicle navigation, mining, farming, and surveying.
Affordability Issues	Mapping data source, worldwide coverage, and accuracy are the key cost drivers.

BACKGROUND

This technology, which uses magnetic map contours for position fixing or navigating, is in its infancy. The sensors are available. The magnetic field data is available in some parts of the world. What is required is to put the parts together along with available correlation processing methods. Magnetic DBRN is not the same as navigating with magnetic heading or magnetic variation, which is a mature technology. Very few countries are investing in DBRN systems using magnetic contour maps.

- Magnetic Data-Based Referenced Navigation (DBRN) Systems[40] when combined with a priori data sources or maps provide a covert or low probability of detection means of obtaining position and direction when the platform is moving. This system uses a pre-stored database that basically provides the earth's magnetic anomaly signature (profile) as a function of Latitude and Longitude coordinates. Units of magnetic field are nanoTesla (nT). For instance, magnetic data on maps consists of connecting equal points of differences of noise level (sensitivity) in nT. For all cases of DBRN systems, there is a computation and correlation process with a star catalog, a pre-surveyed database or a map used as the reference for comparing sensor information profiles to determine position. Accurate time is required for computation and data resolution. Figure 16.310 describes a conceptual DBRN system where the sensor for a Magnetic DBRN can be a magnetometer. Refer to Section 16.4 for magnetometer sensors. Underwater electric field sensors are

[40] The Wassenaar Arrangement's definition of 'Data-Based Referenced Navigation' (DBRN) Systems is "systems, which use various sources of previously measured geo-mapping data integrated to provide accurate navigation information under dynamic conditions. Data sources include bathymetric maps, stellar maps, gravity maps, magnetic maps or 3-D digital terrain maps."

evolving with the advent of the potassium magnetometer, which detects changes in the electric dipole potential (EDP) magnetic field. This provides an alternate method from magnetic sensors of detecting underwater objects. See Section 16.4 for underwater electric field sensors and active electromagnetic sensors.

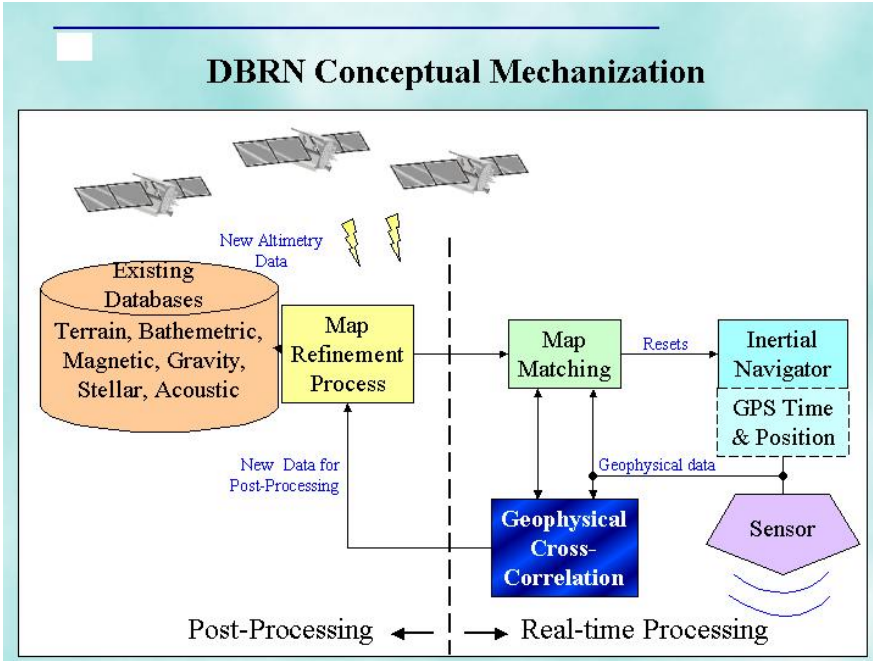

Figure 16.3-10. Conceptual Description of a DBRN Systems (Source: ARL, PennState)

The Magnetic DBRN systems that use this data source can be used for underwater navigation, land navigation or air navigation.

Geospatial Information and Services (GI&S) is the new term for Mapping, Charting and Geodesy (MC&G). Enclosure 1 to JCS MTNTP has a complete explanation of GI&S. Geographic Information Systems (GIS) is a tool to view and manipulate and data. GI&S incorporate the processes that collect, manage, extract, store, disseminate, and exploit geographic information and imagery. A GIS is essentially a computer program. Geophysical grid data is derived from the data collected by the relevant survey magnetic sensor.

DSTL DATA SHEET 16.3-16. GRAVITY DATA-BASED REFERENCED NAVIGATION (DBRN) SYSTEMS AND DATA SOURCES

Technology Parameter(s)	In the next 5 to 10 years, the following will have the potential to significantly enhance or degrade U.S. military capabilities: 1. Gravity Data-Based Referenced Navigation System (DBRN) having the following characteristics: a. Surface, airborne or space position accuracy of less (better) than 100 m CEP. b. Underwater position accuracy of less (better) than 250 m CEP.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Unique computer test models for optimization of database manipulation and extraction.
Unique Software	Algorithms for image correlation and pattern recognition. Integration and data-analysis algorithms and verified data. • Source code, algorithms, and verified data needed to meet above critical parameters.
Major Commercial Applications	Ground-vehicle navigation, aircraft navigation, underwater-vehicle navigation, mining, farming, and surveying.
Affordability Issues	Mapping data source, worldwide coverage, and accuracy are the key cost drivers.

BACKGROUND

Gravity Data-Based Referenced Navigation (DBRN) Systems[41] when combined with a priori data sources or maps provide a covert or low probability of detection means of obtaining position and direction when the platform is moving. This system uses a pre-stored database that basically provides the earth's gravity value (profile) as a function of Latitude and Longitude. The Gravity DBRN system on the platform would either use a gravimeter sensor to read the gravity value, or compute the gravity value from other sensors, i.e., subtracting acceleration data from inertial navigation systems from acceleration from GPS data. As the platform moves, the gravity profile (milligals), Latitude, and Longitude is correlated with the pre-stored database. One milligal (mGal) is approximately equal to one millionth of the earth's gravity field. The strength of the earth's field is 980,000 mGal, therefore 1 mGal is approximately 1 microG and one milligal is approximately the presently achievable precision of gravity measurements at sea on a moving platform. The profile of the gravity signal is correlated with the pre-stored database. Correlation of the profile of the gravity signature with the pre-stored database will determine the platform's position. Continuous determination of position over time will provide direction from which, with time, will provide other navigation information, such as velocity and distance traveled.

Gravity gradiometers measure gravity gradient (derivatives of, or spatial change of gravity acceleration) in units of Eotvos. Areas where the gravity signal changes most rapidly (large gradients and rapid changes in gradient) are where this system operates best. Figure 16.3-11 describes a conceptual DBRN system where the sensor for a Gravity DBRN can be a gravimeter. Refer to Section 16.2 for gravity sensors.

[41] The Wassenaar Arrangement's definition of 'Data-Based Referenced Navigation' (DBRN) Systems is "systems, which use various sources of previously measured geo-mapping data integrated to provide accurate navigation information under dynamic conditions. Data sources include bathymetric maps, stellar maps, gravity maps, magnetic maps or 3-D digital terrain maps."

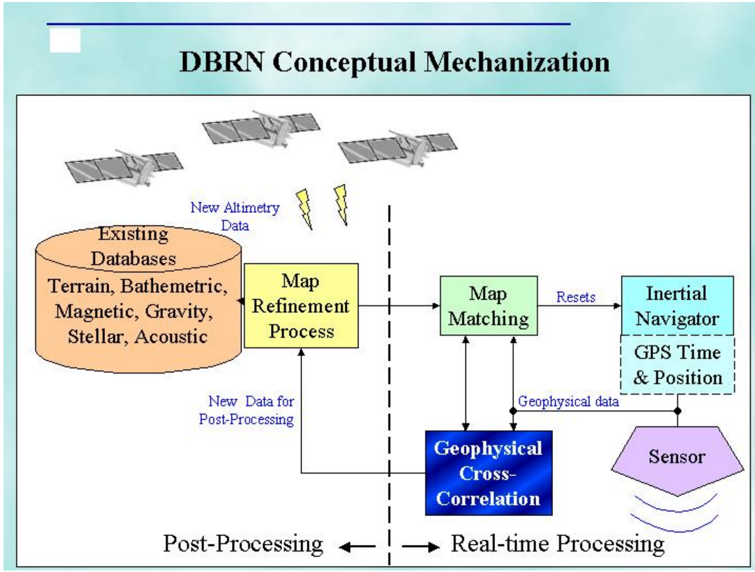

Figure 16.3-11. Conceptual Description of DBRN Systems (Source: ARL, Penn State)

Figure 16.3-12 describes a conceptual DBRN system where the sensor for a Gravity DBRN can be a gravimeter or gradient gravimeter.

Gravity data on maps consists of connecting equal differences of the strength of the gravitational field (usually reported in milligals) and the gravitational field gradient (or gravity gradient, typically in Eotvos). The gradiometer measures the spatial rate of change of gravity and the units for that is Eotvos. One Eotvos is equal to 10^{-9}cm/sec^2/cm, which is a measure of gravity change (cm/sec^2) over a distance (cm). One Eotvos unit is equivalent to the gravity gradient resulting from a change of 0.1 milligal in gravity acceleration over a distance of one kilometer. Gravity data sources apply to both sea floor and surface. The DBRN systems that can use this data source can be either underwater, on surface vessels, land vehicles or aircraft.

SECTION 16.4—MAGNETIC AND ELECTROMAGNETIC SENSOR SYSTEMS

Highlights

- Magnetic and electromagnetic sensor technology varies greatly with type, application, and cost.
- Magnetic and electromagnetic sensor systems and arrays provide a covert detection and classification technology with increased attitude determination and detection and location of submarines, mines, and mobile missiles.
- Knowledge of position, GNSS time, and better computational capabilities using optical processing/correlation will greatly enhance magnetic and electromagnetic array detection performance.
- Anticipate more use of low-cost MEMS, thin-film and nanotube magnetic resistive (MR) sensors for a number of applications for which cost, size, and power are driving factors, such as mine detection and area security.
- Potassium and helium-4 (He-4) optically pumped magnetometers are demonstrating performance comparable to superconductive quantum interference device (SQUID) magnetometers at lower cost and without the logistic complication of maintaining superconductive temperatures.
- Biomedical research and diagnostics and nondestructive evaluations are major military funding applications for future usage of SQUID sensors. The ability to accurately characterize nanotubes will help scientists and engineers develop devices that use nanotubes to their full potential.
- The accuracy of magnetic gradiometers, utilizing either the SQUID or potassium technologies, nearly eliminates the natural geomagnetic background noise.
- High superconducting temperature (T_c) SQUID technology has matured since its inception in 1987 to the point where nitrogen-cooled superconducting sensors are rivaling their low T_c counterpart.
- Underwater electric field sensors are evolving with the advent of the potassium magnetometer, which detects changes in the electric dipole potential (EDP) magnetic field. This provides an alternate method from magnetic sensors of detecting underwater objects.
- Magnetic sensor use for nondestructive testing and inspection of vehicle integrity will increase.

OVERVIEW

This section covers the technology relative to magnetic and electromagnetic sensors. Magnetic sensor systems detect and display the presence of a magnetic field and measure its magnitude and/or direction. Electric Field sensors have been designed to detect remote measurements of electric fields. Every object has a distinct magnetic signature that is reflected or emitted from the object. The common problem in magnetometry and electric field measurement is the detection and classification of the signature or, in other words, getting the signal out of the noise. This unique and enabling technology can be used to detect and locate an adversary, detect magnetic heading, or, if mobile, determine own position by correlation with a database reference. Magnetic sensors of special interest include SQUIDs, nuclear precession, optically or laser pumped, flux gate, fiber-optic, MR, and induction coil. Some magnetometer literature often states sensitivity in micro gauss where one micro gauss equals 0.1 nTesla.

Magnetic sensor systems can be configured to detect the spatial variation of the magnetic field intensity (i.e., the gradient of the magnetic field intensity) from sources external to the instrument and in this mode are called magnetic gradiometers. Electromagnetic sensors include electric field and active electromagnetic sensors. This section will discuss synthetic and intrinsic gradiometers and arrays. For details on Magnetic Data Based Referenced Navigation (DBRN), see Section 16.3.

BACKGROUND

Fluxgate magnetometers have been used for sensing magnetic north since World War I. Submarine detection during World War II was one of the first applications of fluxgate magnetometers for detection. The nuclear precession magnetometer was also an outgrowth of the war research of nuclear magnetic resonance (NMR). Magnetic gradiometers can consist of two magnetic sensors or a single intrinsic magnetic gradient sensor. For a more complete description of magnetometers, magnetic gradiometers and magnetic anomalies see *Applied Geophysics.*[42] For further understanding of geomagnetism see http://www.ngdc.noaa.gov/seg/potfld/geomaginfo.shtml and http://www.britannica.com/bcom/eb/article/5/0,5716,51255+1,00.html.

Magnetic heading can be sensed by a flux value or computed by subtracting magnetic variation from a database from the true heading sensed by an INS. Magnetic variation is obtained from a map database and can be used in many formats and accuracy levels. The use of true heading versus magnetic heading by the majority of navigation applications has vastly increased in the past 10 years by the use of INS and GPS in military and commercial applications. With computational techniques, databases with prior or real-time magnetic field data from magnetometer arrays can be used to reduce the spatial and temporal background noise in the detection of land vehicles, submarines, or mines. Increasing the signal-to-noise (SNR) of magnetic sensors is a major factor in improving magnetic applications by the military.

42 *Applied Geophysics,* Second Edition, by Telford, Gelhart, and Sheriff, Cambridge University Press, 1990.

LIST OF DSTL TECHNOLOGY DATA SHEETS
16.4. MAGNETIC AND ELECTROMAGNETIC SENSOR SYSTEMS

Magnetic Sensors

Electromagnetic Sensors

DSTL DATA SHEET 16.4-1. MAGNETOMETERS—SUPERCONDUCTING QUANTUM INTERFERENCE DEVICES

Technology Parameter(s)	In the next 5 to10 years: 1. Noise level < 20 picotesla (pT) rms/√Hz.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient < 0.1 nT/meter. Ability to control external field amplitude and variations to sensitivity of test magnetometer. Specially designed nonmagnetic, closed-cycle refrigeration equipment capable of operation to less than 103 K.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement exceeding 10 to 1) for operation on mobile platforms and in stationary arrays. Specifically developed software for magnetic anomaly detection on mobile platforms and in stationary arrays.
Major Commercial Applications	Resource exploration, nondestructive testing, and medical imaging. Chemical array using magnetic tagging.
Affordability Issues	Medical imaging is funding driver.

BACKGROUND

Superconducting magnetometers are a class of devices that use the properties of superconductors in conjunction with SQUIDs, which exploit the magnetic field sensitivity of the Josephson effect.[43] Vector magnetometers employing DC SQUID technology have performances which can exceed 10^{-5} nT. In recent years, SQUID low-frequency magnetic sensors have been evaluated for the detection of the weak magnetic fields generated by the human body. Their use in clinical diagnostic equipment has raised considerable interest. Magnetometers and magnetic gradiometer systems containing SQUID low-frequency magnetic sensing circuits have also been designed for operation outside the laboratory and hospital environments. One of the primary obstacles to the use of SQUID magnetic sensing systems is the need for a cryogenic environment. The low-temperature class of superconductors, which was known before 1986, requires operation at temperatures below about 15 K (–258 °C). In 1987, a new class of high-temperature superconducting materials was discovered. These materials can be used in SQUID sensors that operate at temperatures as high as 80 K (–193 °C—liquid nitrogen temperatures). These high-temperature superconducting materials can be operated with liquid-nitrogen cryogenic enclosure systems, which are much more energy efficient and much less complex than the liquid-helium cryogenic systems required for operation below 15 K. Thus, from the viewpoint of cryogenics, the use of high-temperature SQUIDs is more desirable and logistically more convenient. The sensitivity (noise level) of the high-temperature SQUIDs, which has continually improved over the years, is within an order of magnitude of the best state-of-the-art low-temperature SQUID sensors.

43 http://encarta.msn.com/find/Concise.asp?ti=0109A000

DSTL DATA SHEET 16.4-2. MAGNETOMETERS—OPTICALLY PUMPED/ELECTRON RESONANCE (HELIUM-4, POTASSIUM, RUBIDIUM, OR CESIUM)

Technology Parameter(s)	In the next 5 to10 years: 1. Noise level < 20 picotesla rms/√Hz. 2. Sensitivity 0.005 nT. 3. Resolution 0.01 nT.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient of less (better) than 0.1 nT/m. Ability to control external field amplitude and variations to sensitivity of test magnetometer.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement exceeding 10 to 1) for operation on mobile platforms and stationary arrays. Specially developed software for magnetic anomaly detection on mobile platforms and in stationary arrays.
Major Commercial Applications	Resource exploration and UXO detection.
Affordability Issues	None identified.

BACKGROUND

Resonance magnetometers are a class of magnetometer that uses the shift in the frequency of electron resonance or nuclear resonance to measure external magnetic fields. In general, resonance devices measure only the amplitude (modulus) of the external vector field and are relatively insensitive to orientation. For this reason they are often favored for use on moving platforms.

Electron-resonance magnetometers are sometimes called electron paramagnetic resonance (EPR) magnetometers or, more commonly, optically pumped magnetometers. Outside the United States, they are often called “quantum magnetometers.” Electron-resonance magnetometers work on the principle of optically monitoring the absorption and re-radiation of electron energy levels of atoms in the gaseous state. According to the Zeeman effect,[44] an external field can split electron energy levels into sublevels. The energy difference between the sublevels corresponds to a radio frequency according to Planck’s Law,[45] and it is proportional to the external magnetic field. If radio-frequency energy is introduced by means of a coil, at the proper frequency, transitions can be induced between the sublevels. This population change in substates results in the optical pump doing some work to restore equilibrium. By noting the frequency at which absorption of the pump beam occurs, we can determine the amplitude of the external magnetic field. Atomic gases of He-4, potassium, rubidium, or cesium are commonly used in optically pumped magnetometers. (In an Earth field of 50,000 nT, a potassium magnetometer would operate at a radio-frequency resonance of 350 KHz, while a helium magnetometer would operate at 1.4 MHz.)

44 http://wadhwa.home.cern.ch/wadhwa/zeeman.html

45 http://www.britannica.com/bcom/eb/article/xref/0,5716,10173,00.html

DSTL DATA SHEET 16.4-3. MAGNETOMETERS—NUCLEAR PRECESSION (PROTON/OVERHAUSER/HELIUM-3)

Technology Parameter(s)	In the next 5 to 10 years: 1. Noise level < 20 picotesla rms/√Hz.
Critical Materials	Buffering fluid for Overhauser magnetometer.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient of less (better) than 0.1 nT/m. Ability to control field amplitude and variations to sensitivity of test magnetometer.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement exceeding 10 to 1) for operation on mobile platforms and in stationary arrays. Specially developed software for magnetic anomaly detection on mobile platforms.
Major Commercial Applications	Resource exploration.
Affordability Issues	Not an issue.

BACKGROUND

Resonance magnetometers are a class of magnetometers that use the shift in the frequency of nuclear resonance or electron resonance to measure external magnetic fields. In general, resonance devices measure only the amplitude (modulus) of the external vector field and are relatively insensitive to orientation. For this reason, they are often favored for use on moving platforms.

Magnetometers utilizing nuclear resonance are commonly known as nuclear-precession magnetometers or NMR magnetometers. Principal NMR devices are the proton-precession magnetometer, the Overhauser proton magnetometer, and the He-3 magnetometer. In all three devices, the nuclear magnetic moments are first polarized and then allowed to precess around the external field vector. The precession frequencies are atomic standards proportional to the amplitude of the external field. The precession frequency is picked up by coils and counted to obtain a measure of field amplitude. In Earth field (approximately 50,000 nT), the proton-precession magnetometer and Overhauser devices have precession frequencies of about 2,000 Hz, and the He-3 device about 1,700 Hz. In the proton-precession magnetometer and Overhauser magnetometers, the precessing nuclei are usually in hydrocarbon fluids. In the case of the He-3, the nuclei are in a gas-filled cell. The proton-precession magnetometer is polarized by a DC field for a period of 200–1,000 milliseconds during each operating cycle. Field measurements are normally obtained no more often than every 2.0 seconds. Practical proton-precession magnetometer noise levels are about 100 picotesla per root Hertz at a frequency of 0.1 Hz. Typical average power consumption is 2.0 W or more at maximum cycle rates. In the Overhauser proton magnetometer, the protons are polarized by a radio frequency "pump" (approximately 80 MHz) acting through a buffer solution. This device can be operated continuously, unlike the proton-precession magnetometer. Practical noise levels of Overhauser magnetometers are 10 picotesla per root Hz at frequencies of 0.1 Hz and 1.0 Hz and 10 picotesla per root Hz at frequencies of 0.1 Hz and 1.0 Hz. Power consumption can be 1.0 W or less. In the He-3 magnetometer, polarization is achieved by an optical pump. It can be operated continuously and has potential for low noise (1.0 picotesla per root Hz at a frequency of 0.1 Hz). This magnetometer can be operated at power levels of 0.5 W or lower.

DSTL DATA SHEET 16.4-4. MAGNETOMETERS—INDUCTION COIL

Technology Parameter(s)	In the next 5 to 10 years: 1. Noise level < 50 picotesla rms/√Hz at frequencies less than 1 Hz. < 1 picotesla rms/√Hz at frequencies between 1 Hz and 10 Hz. < 0.1 picotesla rms/√Hz at frequencies exceeding 10 Hz.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient of less (better) than 0.1 nT/m. Laboratory capability of less (better) than 10^{-6} nT rms per square root Hz at 1 kHz. Ability to control field amplitude and variation to sensitivity of test magnetometer.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement exceeding 10 to 1). Specially developed software for magnetic detection, active electromagnetic detection, and ELF/VLF communication.
Major Commercial Applications	Resource exploration.
Affordability Issues	Not an issue.

BACKGROUND

Induction-coil magnetometers are a class of devices that contain a conventional wire coil, often surrounding a permeable core that measures the time rate of change of magnetic field intensity in a direction parallel to the coil axis (Faraday induction). The sensitivity of each sensor is determined by the effective area and the number of turns of the detection coil and by the magnetic flux density threading the coil. The high-permeability metal core enhances the magnetic flux density. Induction-coil magnetometers are useful for sensing AC magnetic fields or the relative motion of magnetic objects.

DSTL DATA SHEET 16.4-5. MAGNETOMETERS—FLUX GATE

Technology Parameter(s)	In the next 5 to 10 years: 1. Noise level < 10 picotesla rms/√Hz at frequency of 1 Hz.
Critical Materials	Special core materials and material processing.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient of less (better) than 0.1 nT/m. Ability to control field amplitude and variations to sensitivity of test magnetometer.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement exceeding 10 to 1) for operation on mobile platforms and in arrays. Specially developed software for magnetic-anomaly detection in mobile platforms.
Major Commercial Applications	Aircraft, land vehicles, and ships for magnetic compass system input. Resource exploration and UXO protection. Spacecraft attitude determination.
Affordability Issues	Not an issue.

BACKGROUND

Flux-gate magnetometers are a class of devices that consist of windings on a ferromagnetic core, the magnetic saturation of which is a function of magnetic-field strength. An applied magnetic field in combination with the drive field produces even harmonics of the drive frequency that are proportional to the strength of the external magnetic field along the core axis. Oriented flux-gate magnetometers have three mutually orthogonal flux-gate sensors that are continuously oriented, so that two of the axes maintain zero field, and the third is oriented parallel to the ambient field direction. Flux-gate sensing elements are typically in the shape of cylinders or rings with lengths or diameter about 2–4 cm. A flux-gate magnetometer was used for attitude stabilization in Sputnik.[46]

[46] http://www.izmiran.rssi.ru/magnetism/Petrov/dolgino_rep.html

DSTL DATA SHEET 16.4-6. MAGNETOMETERS—FIBER OPTIC

Technology Parameter(s)	In the next 5 to 10 years: 1. Noise level < 0.8 nT rms/√Hz.
Critical Materials	None identified
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient of less (better) than 0.1 nT/m. Ability to control field amplitude and variations to sensitivity of test magnetometer
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement exceeding 10 to 1) for operation on mobile platforms and in arrays. Specially developed software for magnetic-anomaly detection in mobile platforms.
Major Commercial Applications	Aircraft, land vehicles, and ships for magnetic compass system input. Resource exploration and UXO protection.
Affordability Issues	Not an issue.

BACKGROUND

Fiber-optic magnetometers are a class of devices that measures magnetic fields by exploiting the difference in optical path length between an optical fiber that is mounted on a magnetostrictive material and an unclad fiber-optic cable. The sensor operates in a frequency range from DC to 60 kHz. The sensor size depends on the sensitivity required. Fiber-optic magnetometers and fiber-optic intrinsic magnetic gradiometers are used to implement unobtrusive and remotely operable magnetic intrusion sensors for military and civilian secure-facility protection and for detection of the presence of metal objects such as weapons in the vicinity of designated security zones.

DSTL DATA SHEET 16.4-7. MAGNETOMETERS—MEMS AND MAGNETORESISTIVE

Technology Parameter(s)	In the next 5 to 10 years: 1. Noise level < 0.03 nT rms/√Hz.
Critical Materials	Materials and manufacturing techniques.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient of less (better) than 0.1 nT/m. Ability to control field amplitude and variations to sensitivity of test magnetometer. Electroplating of ferromagnetic films
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement exceeding 10 to 1) for operation on mobile platforms and in arrays. Specially developed software for magnetic-anomaly detection on mobile platforms and in arrays.
Major Commercial Applications	Disk drive read heads, vehicle detection, resource exploration, and nonvolatile memory.
Affordability Issues	Not an issue.

BACKGROUND

MEMS have the potential for low cost and power magnetic sensors. MR magnetometers measure the electrical resistance of a material in response to a magnetic field. The magnetic field modulates the scattering of conduction electrons in metals. This effect can be exploited in numerous magnetic sensor devices and applications, such as MR read heads, position sensor, bio-magnetic measurement, MR random-access memory, and general magnetic field sensors. MR magnetometer literature often states sensitivity in micro gauss where one micro gauss equals 0.1 nTesla.

DSTL DATA SHEET 16.4-8. MAGNETIC GRADIOMETERS

Technology Parameter(s)	In the next 5 to 10 years: 1. Noise level of < 0.015 nT/meter rms/√Hz.
Critical Materials	Same as underlying magnetometer technology.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient of less (better) than 0.1 nT/m. Ability to control external field amplitude and variations to sensitivity of test magnetometer.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement exceeding 10 to 1) for operation on mobile platforms and in arrays. Specially designed software for magnetic-anomaly detection on mobile platforms and in arrays.
Major Commercial Applications	Detection of UXO, buried drums, tanks, etc., SQUID gradiometer arrays for medical-biological research.
Affordability Issues	Not an issue.

BACKGROUND

Magnetic gradiometers measure the rate of change of the spatial magnetic gradient. It usually contains a pair of magnetometers placed a specific distance apart. Magnetic gradiometers can be either single axis or multiple axis, depending on sensor orientation and packaging. The three-axis gradiometer is designed for location of buried pipe and cable location.

DSTL DATA SHEET 16.4-9. UNDERWATER ELECTRIC FIELD SENSORS

Technology Parameter(s)	In the next 5 to 10 years: 1. Noise level of less (better) than 10 nanovolt per meter rms per sqrt Hz at 1 Hz.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Manufacturing and electrode conditioning techniques to reduce noise and increase long-term stability/survivability.
Unique Software	Algorithms and verified data for real-time compensation systems for detection (improvement exceeding 10 to 1) and for operation on mobile platforms and in arrays. Specially designed software for conductivity-anomaly detection on mobile platforms and in arrays.
Major Commercial Applications	Resource exploration. Biological and medical sciences, R&D.
Affordability Issues	Not an issue.

BACKGROUND

Electric field sensors have been designed to detect remote measurements of electric fields. Such sensors can be used to safely measure high voltages and to monitor the performance of electrical equipment without having to make a hard electrical contact. Magnetotelluric (MT) sensing is a technique used for investigating the structure and composition of the earth's lithosphere (surface down to about 10 or even 100 km) for geophysics research and oil, gas, water or mineral exploration. Variations in electrical impedance of the earth's crust to naturally occurring electromagnetic waves are calculated and mapped based on surface measurements of preferably both the magnetic and electric fields.

DSTL DATA SHEET 16.4-10. ACTIVE ELECTROMAGNETIC SENSORS

Technology Parameter(s)	In the next 5 to 10 years: 1. Noise level of less (better) than 1.0 picotesla rms per square root Hz per meter.
Critical Materials	Same as underlying magnetometer technology.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient of less (better) than 0.1 nT/m. Ability to control external field amplitude and variations to sensitivity of test magnetometer.
Unique Software	Algorithms and verified data for real-time electromagnetic compensation systems for detection (improvement exceeding 10 to 1) and for operation on mobile platforms and in arrays. Specially designed software for magnetic-anomaly detection on mobile platforms and in arrays.
Major Commercial Applications	Resource exploration.
Affordability Issues	Not an issue.

BACKGROUND

Active electromagnetic sensors are devices that measure and monitor electromagnetic fields in remote locations. They can also monitor electrical equipment and measure high-voltage outputs from transmission lines. Electric field sensing is also a means to track human motion and gestures. They can also be used in determining the location of lightning.

DSTL DATA SHEET 16.4-11. MAGNETIC AND ELECTRIC FIELD SENSOR ARRAYS

Technology Parameter(s)	In the next 5 to 10 years: 1. Noise level of less (better) than 0.05 nT rms per square root Hz. 2. Noise level of any individual magnetometers is less (better) than 0.01 nT rms per square root Hz. 3. Noise level of any electric field sensor of less (better) than 10 nanovolt per meter rms per sqrt Hz at 1 Hz.
Critical Materials	Same as underlying magnetometer technology.
Unique Test, Production, Inspection Equipment	Magnetic contamination control area with field gradient of less (better) than 0.1 nT/m. Ability to control external field amplitude and variations to sensitivity of test magnetometer.
Unique Software	Algorithms and verified data for real-time magnetic compensation and detection (improvement exceeding 10 to 1) for operation on mobile platforms and in arrays. Specially designed software for magnetic anomaly detection on mobile platforms and in arrays.
Major Commercial Applications	Resource exploration and bottom current studies.
Affordability Issues	Not an issue.

BACKGROUND

An array of magnetic and electric sensors can be either stationary or moving. The array improves the signal-to-noise ratio of the individual sensors. Refer to the data sheet for the individual sensor for more information.

SECTION 16.5—PRECISE TIME AND FREQUENCY (PT&F)

Highlights

- The worldwide availability of accurate time via GNSS will increase the combination of communications, imaging, and navigation functions into multi-hybrid sensor systems. This will provide a common grid reference for battlespace data management. The accuracy of the ionosphere model is a limiting factor on GPS time transfer.
- Autonomous and common three-dimensional POSITIME (position and time) grid reference will improve battlespace situational awareness by providing a precise POSITIME tag on all battlespace information collected. This will provide real-time knowledge of the location and movement across the battlespace of allied and enemy assets.
- Accurate time is required for autonomous operation of satellite network geolocation systems and enhanced crypto/transec performance in spread-spectrum communication systems.
- The importance of PT&F has only recently been recognized in military and commercial usage because of the availability of GNSS time. Foreign sources are currently providing the funding engine for future technology improvements in PT&F, as U.S. R&D funding has declined.
- Chip scale atomic clocks about 1 ccm in size are being developed that operate with minute power and have long-term stability characteristics.
- The number of U.S. suppliers of Space Qualified Atomic Frequency Standards has declined to one.

OVERVIEW

This section of PNT is divided into four PT&F technology areas: time distribution, atomic/ion clocks, low-power clocks (multiple applications) and oscillators (used in receivers), and spaceborne clocks (used in ground stations and satellites). See Section 19.1-1 for space qualified clocks. Most types of POS/NAV systems are highly dependent on precise time, whereas most applications are interested more in frequency and not absolute time. See Section 16.1 for inertial navigation and Section 16.3 for radio navigation in general and the GPS, GLONASS and LORAN system in particular. In the future several new GNSS may be operational: Galileo (EU), Beidou (China), and the Geo Augmented Navigation (GAGAN) (India). Beidou uses satellites in geostationary orbit. The first GAGAN satellite, which will provide the space platform for the augmentation system, is scheduled to be launched in 2005-06. The 2001 Federal Radionavigation Plan[47] notes civil timing applications.

BACKGROUND

Throughout history, the notion of time was tied to the variable rotation of Earth. During the 19th century and for a good part of the 20th, the second was defined as 1/86,400 of a "mean solar day," since the length of the day varies throughout the year. With the advent of new requirements such as telecommunications, navigation, and aerospace systems requiring more accuracy for their applications, a more uniform means of keeping time was needed. In the 1940s, scientists discovered that the regular vibration or "resonance" within piezoelectric materials would permit quartz crystal oscillators to drive more accurate and precise clocks than the mechanical drives previously used. Atomic research lead to application of the quantum transitional frequencies in neutral alkali atoms to provide improved timekeeping. Cesium has transitional frequencies that make it particularly useful in a practical clock device. Experimentation with cesium beam frequency standards for timekeeping led to the formation of

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[47] 2001 Federal Radionavigation Plan, DOT-VNTS-RSPA-98-1, DOD-4650.5, pp. 2-30 to 2-32, 3-5. http://www.navcen.uscg.gov/pubs/frp2001/default.htm http://www.navcen.uscg.gov/

Atomic Time and in 1972, the international community redefined the second as 9,192,631,770 periods of the radiation corresponding to transition between two hyperfine levels of the ground state of the cesium 133 atom.

In the 1970s, the U.S. military developed GPS (refer to Section 16.3), which incorporated advancements in high-stability clocks, time-transfer, and 3-D navigation. Deployed in the 1980s, GPS uses both space qualified cesium and rubidium frequency standards in the current satellites, known as Block II/IIA, and space qualified rubidium standards in the replacement satellites, Block IIR.

LIST OF DSTL TECHNOLOGY DATA SHEETS
16.5. PRECISE TIME AND FREQUENCY (PT&F)

DSTL DATA SHEET 16.5-1. TIME AND FREQUENCY DISTRIBUTION SYSTEMS

Technology Parameter(s)	In the next 5 to 10 years: 1. Capable of providing signal phase (time) common synchronization of < 10^{-9} sec, relative to UTC (USNO); intersystem synchronization of < 10^{-8} sec relative to battle group; coordinated use of platform resources for lower cost and robustness; 10^{-9} for interoperability, surveillance, and high-speed communication. Any time-distribution system that has any of the following characteristics: 1. Signal phase (time) communication synchronization of less (better) than 28 ns within 5 min (real time), UTC (USNO). 2. Intersystem synchronization of less (better) than 28 ns relative to other system nodes within 5 min (real time). 3. Local navigation/communication systems capable of time transfer at less (better) than 28 ns, UTC (USNO). Any frequency ($\Delta f/f$) distribution system that has any of the following characteristics: 1. Low-accuracy aircraft/land mobile of 10^{-12}. 2. Intermediate land reference sites of 10^{-13}. 3. Long term autonomous sites of 10^{-13}. 4. Large TDMA systems of 10^{-11}.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Frequency references for calibration with $\Delta f/f < 1 \times 10^{-15}$. Distribution amplifiers having capabilities better than 1 ns noise contribution. Environmentally stabilized GPS timing receiver equipment capable of carrier phase measurements with precisely known phase bias determination.
Unique Software	Algorithms and verified data to combine clock outputs to improve stability/accuracy performance (i.e., “ensembling”) in mobile operations in near real time. Automatically detect phase jumps or frequency perturbations and/or improve reliability from redundancy. Self monitoring.
Major Commercial Applications	Communication systems including cable, cellular, and Internet; electrical power generation and grid management. Electronic commerce and applications that require traceability and involve shared database.
Affordability Issues	Large volume use.

BACKGROUND

Time distributions systems provide synchronous measurements of time within a network of users. Position and Time (POSITIME) have a relationship that has a broad spectrum of applications. Time distribution systems can be (1) worldwide, like GNSS; (2) in a localized area, like LORAN or GNSS augmentation systems; or (3) tailored for unique applications, such as the banking industry. The two worldwide operational systems are the Global Positioning System (GPS) and GLONASS. See Section 16.3 for radio navigation in general and the GPS, GLONASS and LORAN system in particular. In 2003, the U.S. FAA announced the commissioning of its Wide Area Augmentation System (WAAS), which will make GPS suitable for aircraft navigation over the United States.

Advances in computer processing, precise global positioning *(precise time),* and telecommunications will provide the capability to determine accurate locations of friendly and enemy forces, as well as to collect, process, and distribute relevant data to thousands of locations *(timely).* Joint Chief of Staff (JCS) positioning, navigating, and timing policy addresses the need for precise time and time-distribution systems. The Joint Science & Technology plans address the need for information *(precise time and time distribution systems)* superiority, including direct integration of GPS (precise time) with sensor outputs, distributed and collaborative virtual planning in real time, and integrated cross-sensor tracking with unique target ID and real-time updates.

DSTL DATA SHEET 16.5-2. ATOMIC/ION CLOCKS

Technology Parameter(s)	In the next 5 to 10 years: 1. Provide stability and accuracy approaching 1×10^{-15} sec for reference systems.
Critical Materials	Magnetic shields, low-noise (10^{-12} up to less than 100 s) local oscillators, and long-life (10 years) stabilized lasers.
Unique Test, Production, Inspection Equipment	Precision-milling machining, especially in the microwave cavity.
Unique Software	Algorithms and verified data to combine clock outputs to improve stability/accuracy performance (i.e., "ensembling"). Algorithms and software for digital control of internal servo, optimization, and self-diagnostic controls.
Major Commercial Applications	Satellites, synchronization of communication and navigation systems, power-transmission management, secure frequency-hopping communication. Geophysical and military distribution sensor system (arrays).
Affordability Issues	Space-qualified units quantity requirements are low internationally. The number of U.S. space-qualified atomic frequency standard suppliers is declining and may be down to one within 5 years. There is a high demand in telecom market for rubidium standards.

BACKGROUND

Atomic clocks are composed of three general modules: a crystal oscillator, the atomic physics package, and the supporting electronics. Essentially an atomic clock uses an atomic material, such as rubidium or cesium that is irradiated with electromagnetic radiation; causing the atom to switch its hyperfine state. The frequency of the radiation causing the transition becomes the regular beat that the clock counts to register time, or 9,192,631,770 oscillations per second in the case of cesium. A bibliography of Rubidium clock references is referenced.[48] The fundamentals of atomic clocks are noted in reference.[49]

48 http://cfa-www.harvard.edu/~dphil/work/rubidiumbib.html

49 http://science.howstuffworks.com/atomic-clock1.htm

DSTL DATA SHEET 16.5-3. LOW-POWER CLOCKS AND OSCILLATORS

Technology Parameter(s)	In the next 5 to 10 years: 1. Provide accuracy and stability typical of current cesium and rubidium clocks at greatly reduced weight and power. Any low-power clocks or oscillators specially designed for positioning or navigation and specially designed components therefore having any of the following characteristics: 1. Long-term stability (aging) better than 1 □ 10^{-11}/month with less than 1 W power consumption, or 2. Any crystal oscillator capable of operation at g levels greater than 10,000 g.
Critical Materials	Low-powered, stabilized laser diodes; battery technology; and vertical-cavity surface-emitting diodes.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Operating software for control of the clock.
Major Commercial Applications	Synchronization of communication and navigation systems, power transmission management, secure frequency-hopping communication.
Affordability Issues	Large volume potential.

BACKGROUND

Throughout the past 20 or so years, there have been developments in crystal oscillators for frequency control and timing applications (http://www.rakon.co.nz/generated/1-25/2.html). A crystal oscillator is a part of a clock, but the clock has additional electronics to assign or make time from the oscillator pulses. (Figure 16.5-1 shows a basic clock/oscillator diagram.) The term "clock" is often used interchangeably with "oscillator," but there are differences. Development work is ongoing for oscillators that take as little power as possible so they may be used in battery-powered handheld radios and the like, but they are often called clocks.

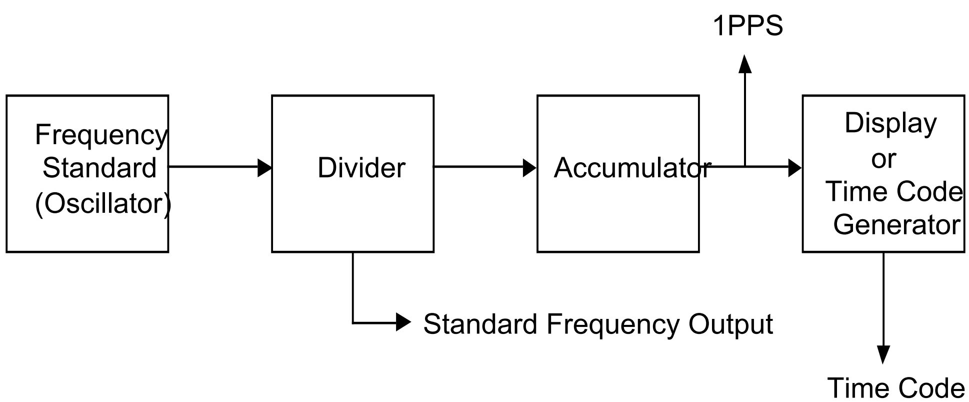


Figure 16.5-1. Basic Clock/Oscillator Description

DSTL DATA SHEET 16.5-4. OPTICALLY PUMPED AND OPTICAL CLOCKS

Technology Parameter(s)	In the next 5 to 10 years: 1. Provide stability and accuracy approaching 1×10^{-16} sec for reference systems. 2. Long-term stability (aging) less (better) than 1×10^{-11}/month. 3. Being space qualified. 4. Having a noise level sensitivity of lower (better) than 20 pT (rms) per square root Hz.
Critical Materials	Single isotope Rubidium (Sources are US and Russia), long-life, mode locked and stabilized laser diodes, Radiation hardened, Optical Fibers, Optical Components, Optical Comb Filter Fiber Materials, Femto-second laser pulse generators.
Unique Test, Production, Inspection Equipment	Optical Comb Filter Fibers are uniquely produced.
Unique Software	None identified.
Major Commercial Applications	Satellites, Telecommunications, synchronization of communication and navigation related systems, and power-transmission management
Affordability Issues	Beyond capabilities of most countries—low volume.

BACKGROUND

The current generation of cesium atomic clocks has an accuracy of one part in 10^{15}—equivalent to an error of less than 1 second in 30 million years. This accuracy can be improved by several orders of magnitude if optical clocks are used.[50] The key element of optical interrogation or optical metrology is a frequency-stabilized mode locked laser which is locked to a selected frequency of neutral atoms chosen for the standard. For optical frequency synthesis or use as an optical clock, the generation of femto-second pulses from the laser is necessary.

[50] http://beta.physicsweb.org/article/news/5/5/16

SECTION 16.6—BIOLOGICAL NAVIGATION SYSTEMS

Highlights

- Biological navigation technologies will enable intelligent autonomous vehicles (IAVs) and tactical mobile robots (TMRs) to navigate over long or short distances using navigation techniques similar to those of humans and animals, i.e., the biological senses of smell, touch, vision, hearing or taste.
- Currently, this technology is at a similar stage of development as aviation technology was during World War I. However, the goal to have limited capability IAVs and TMRs in military-use before 2025 is achievable in harsh conditions such as extreme heat or cold, or to operate in chemically, biologically, or radiologically contaminated environments.
- In the foreseeable future, warfighter-robot integration will be the critical issue for most military applications. While positive efforts are underway in both DARPA and Project Alpha, no single joint authority exists to fund, direct, integrate, test and evaluate DoD research and development activities into meaningful integrated warfighter/robotic teams for future applications.

OVERVIEW

Biological navigation refers to the ability to navigate autonomously over long or short distances using the biological five senses (see, hear, smell, touch and taste). This section addresses all five of the following biological navigation technologies (stereovision, audio, odor, tactile and taste (salt)) that have potential to enhance military capabilities in the future, particularly in intelligent autonomous vehicles (IAV) or tactical mobile robots (TMR). Intelligent navigation algorithms are also addressed because like the human brain, they are essential in integrating all these biological sensors and information to navigate a robot or unmanned vehicle through a complex and changing environment. Two other senses that animals seem to have to help them navigate are gravitation and magnetic senses, which are discussed in Section 16.2 and 16.4, respectively. Section 16.3 addresses both acoustic navigation using echo finders such as sonar and vision navigation systems using communication links such as the Mars pathfinder or image matching terrain data bases.

BACKGROUND

Navigation systems for IAV or TMR will generally have no power, control or computing connection to the outside world and operate in hostile environments. The systems will use navigation techniques similar to those of humans or animals. As humans, we enjoy the luxury of having an amazing computer, the brain, and thousands of sensors to help navigate and interact with the real world. In order to navigate successfully, we make high-level navigation decisions, such as how to get from point A to point B, as well as low-level sub-conscious navigation decisions, such as how to pass through a doorway. Even without all of our sensors, we are able to cope with familiar and unfamiliar environments. For example, blind people can maneuver through unfamiliar areas with the aid of seeing-eye dogs, canes, or audio GPS mapping systems. They cope only because they use external assistance.

The abilities of modern robots stand in stark contrast to human abilities. However, significant advances in robotics have occurred over the past ten years for use in military operations. The recent uses of the Predator unmanned air vehicle in combat, not only for surveillance but also for search and destroy missions shows the capability of robots. But, the Predator is connected to a human. In the future, the TMR will be completely autonomous, having no control or computing connection to the outside world. This section addresses those navigation technologies required to support the next generation of tactical military robots as shown in Figure 16.6-1.

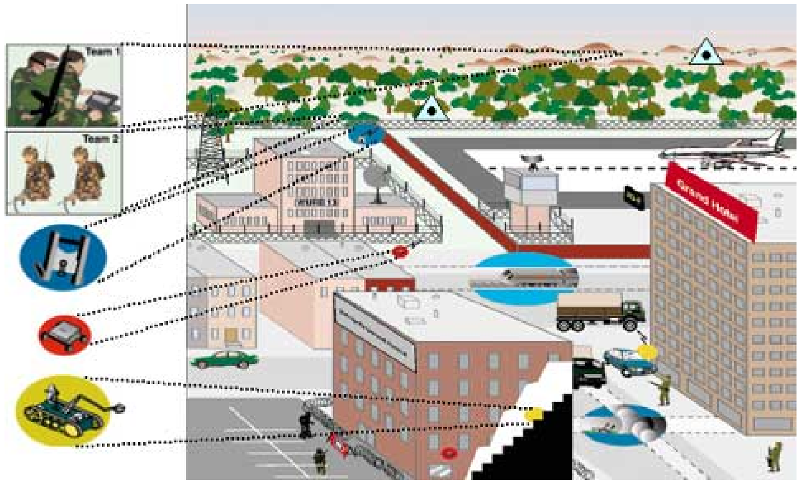


Figure 16.6-1. Concept of Using Tactical Mobile Robots in an Urban Environment (Source: DARPA http://web-ext2.darpa.mil/ato/PROGRAMS/tmr.htm)

LIST OF DSTL TECHNOLOGY DATA SHEETS
16.6. BIOLOGICAL NAVIGATION SYSTEMS

DSTL DATA SHEET 16.6-1. STEREOVISION NAVIGATION

Technology Parameter(s)	In the next 5 to 10 years, the following will have the potential to significantly enhance military capabilities: 1. An autonomous vision based navigation system for tactical mobile robots providing day/night and all-weather capability. 2. Navigation of less than 10 meters CEP.
Critical Materials	Low power optical sensors. Micro-energy source over long time periods. Lightweight materials and high-torque miniature motors.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	An adaptive 'learning' vision algorithm.
Major Commercial Applications	Search and rescue.
Affordability Issues	Continued research necessary. Miniaturization of sensors required for next generation.

BACKGROUND

Stereoscopic vision (or as it is more commonly known, stereovision or depth perception) is the ability to see three-dimensionally or to see length, width, and depth (distance) at the same time. This requires two views of a single object from two slightly different positions. Most people have the ability to see three-dimensionally. Whenever an object is viewed, it is seen twice—once with the left eye and once with the right eye. The fusion or blending together of these two images in the brain permits the judgment of depth or distance.[51]

Stereovision navigation in this data sheet refers to the ability to autonomously navigate using imagery sensors (laser or stereo cameras), with or without a priori navigation databases, gyroscopes, accelerometers, odometers, or star trackers (for use on planetary exploration). For Vision Navigation Systems using RF (human intervention) refer to Data Sheet 16.3-9.

51 http://www.map-reading.com/apident.php

DSTL DATA SHEET 16.6-2. AUDIO NAVIGATION

Technology Parameter(s)	In the next 5 to 10 years, the following will have the potential to significantly enhance military capabilities: 1. An autonomous audio based navigation system providing direction within 30 degrees. 2. Navigation of less than 10 meters CEP.
Critical Materials	Low power audio sensors. Micro-energy source over long time periods. Lightweight materials and high-torque miniature motors.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	An adaptive ‘learning’ audio algorithm.
Major Commercial Applications	Search and rescue, navigation systems for the blind.
Affordability Issues	Continued research necessary. Miniaturization of sensors required for next generation.

BACKGROUND

Audio navigation is the ability for an IAV or MR to navigate by hearing a target’s particular sound pattern, i.e., voice or other unique sound characteristics, and navigating autonomously towards that sound. Auditory sensors include microphones arranged in a Cartesian coordinate reference. For additional information on acoustic, sonar, or bathymetric navigation systems refer to Section 16.3.

DSTL DATA SHEET 16.6-3. ODOR NAVIGATION

Technology Parameter(s)	In the next 5 to 10 years, the following will have the potential to significantly enhance military capabilities: 1. Ability to detect a variety of different nuclear, biological, and chemical (NBC) agents. 2. Ability to measure velocity and direction of NBC plumes at low velocities.
Critical Materials	Low power sensor materials for detecting multiple types of NBC agents. Micro-energy source over long time periods. Lightweight materials and high-torque miniature motors.
Unique Test, Production, Inspection Equipment	Tooling and production equipment to build sensor for detecting multiple types of NBC agents.
Unique Software	An adaptive 'learning' ordor algorithm.
Major Commercial Applications	Search and rescue, medical.
Affordability Issues	Continued research necessary. Miniaturization of sensors required for next generation.

BACKGROUND

Odor navigation refers to the ability for an IAV or TMR to navigate by sense of smell to a particular target. Research in animals has shown this ability. This data sheet discusses use of this technology in Urban Warfare and Chemical/Biological Warfare.

Smell in robots is not yet as refined as that of humans, nor does it need to be. Robotic sensors can detect specific gases including gases that humans cannot smell. One of the most important uses of smelling robots is in airports, detecting fumes from explosives hidden in luggage and shoes.[52]

[52] http://www.thetech.org/exhibits/online/robotics/universal/page10.html

DSTL DATA SHEET 16.6-4. TACTILE NAVIGATION

Technology Parameter(s)	In the next 5 to 10 years, the following will have the potential to significantly enhance military capabilities: 1. Ability to detect and avoid stationary or moving objects. 2. Ability to detect and avoid heat. 3. Ability to detect different surface features of an object.
Critical Materials	Low power sensors. Micro-energy source over long time periods. Lightweight materials and high-torque miniature motors.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	An adaptive 'learning' tactile algorithm.
Major Commercial Applications	Navigation for the blind, commercial robotics.
Affordability Issues	Continued research necessary. Miniaturization of sensors required for next generation.

BACKGROUND

Tactile or touch sensors, are feelers, contact switches and bump sensors that let a robot know when it has made contact with walls or objects. Piezoelectric material is also used in touch sensors because such crystals respond to pressure with a small electric voltage that can detect vibration, impact, or even heat.

For mobile robots tactile sensors can be in the following categories:

1. Tactile feelers (antennae) such as wires.
2. Tactile bumbers such as contact switches.
3. Distributed surface arrays such as switches arranged to provide shape information and sometimes pressure.

DSTL DATA SHEET 16.6-5. TASTE NAVIGATION

Technology Parameter(s)	In the next 5 to 10 years, the following will have the potential to significantly enhance military capabilities: 1. Ability to correct speed of sound variable in calculating a vehicle's position using an underwater acoustic positioning system.
Critical Materials	Low power sensors. Micro-energy source over long time periods. Lightweight materials and high-torque miniature motors.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	An adaptive 'learning' taste algorithm.
Major Commercial Applications	Commercial fishing.
Affordability Issues	Continued research necessary. Miniaturization of sensors required for next generation.

BACKGROUND

This data sheet has limited possibilities, but is being retained as a placeholder for future research. Taste navigation refers to the ability for an IAV or TMR to navigate by tasting the environment. Taste sensors can detect the saline levels in seawaters that can aide an underwater-unmanned vehicle to navigate to a particular known location of saline level. Underwater acoustic positioning systems depend on knowing the speed of sound in water to determine its position. The speed of sound in water varies depending on the saline levels. An underwater vehicle's sensor that can detect the saline levels can provide better and more accurate speed of sound for determination of the vehicle's position.

The mechanism of taste in mammals begins with the taste buds (sensors) on the tongue. Sweet receptors are mostly found on the tip of the tongue, sour receptors on the sides, salty on the tip and frontal sides, and bitter on the back of the tongue. Each taste bud contains roughly 50 to 150 taste receptor cells that act like tiny taste interpretation machines. Proteins on the surface of these cells bind to substances, recognize them, and switch the cells "on" by prompting them into an active state. The cells then transmit information to nerve cells that relay the data to the taste centers of the brain cortex.[53]

For more information on taste sensors refer to http://ultrabio.ed.kyushu-u.ac.jp/A9912/katudo/ajisensor/index_e.html

[53] http://www.nidcr.nih.gov/NewsAndReports/ResearchDigest/May1999A1.htm

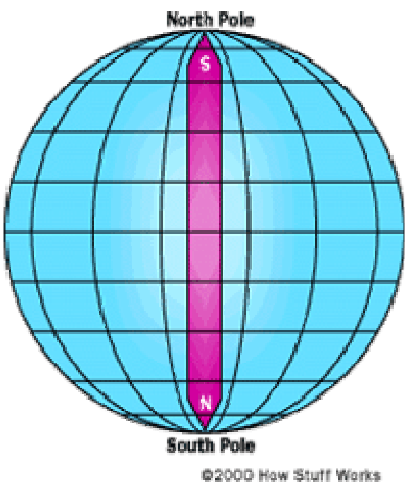
DSTL DATA SHEET 16.6-6. MAGNETIC NAVIGATION

Technology Parameter(s)	In the next 5 to 10 years, the following will have the potential to significantly enhance military capabilities: 1. Detect headings of mobile robots within 10 arc minutes in both indoor and outdoor environments.
Critical Materials	Low power sensors. Micro-energy source over long time periods. Lightweight materials and high-torque miniature motors.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Major Commercial Applications	Surgical navigation.
Affordability Issues	Continued research necessary. Miniaturization of sensors required for next generation.

BACKGROUND

Biological magnetic navigation refers to the ability of a robot to navigate by sensing the earth's magnetic field. Refer to Section 16.4 for more detail information on magnetic sensors. Refer to Section 16.3 on magnetic data based referenced navigation (DBRN).

Navigating by the earth's magnetic field is currently done by two methods: (1) a simple compass or (2) detecting the magnetic field and comparing it with a priori magnetic data base with local positioning data. This data sheet is concerned with the biological sensing of the magnetic field.



A magnetic compass is an extremely simple device as opposed to a gyroscopic compass. (Refer to Section 16.1) It consists of a small, lightweight magnet balanced on a nearly frictionless pivot point. The magnet is generally called a needle. One end of the needle is often marked "N," for north, or colored in some way to indicate that it points toward north as shown in the figure on the right.

The reason why a compass works is more interesting. It turns out that you can think of the Earth as having a gigantic bar magnet buried inside. In order for the north end of the compass to point toward the North Pole, you have to assume that the buried bar magnet has its south end at the North Pole, as shown in the diagram at the right. If you think of the world this way, then you can see that the normal "opposites attract" rule of magnets would cause the north end of the compass needle to point toward the south end of the buried bar magnet. So the compass points toward the North Pole.

To be completely accurate, the bar magnet does not run exactly along the Earth's rotational axis. It is skewed slightly off center. This skew is called the declination, and most good maps indicate what the declination is in different areas (since it changes a little depending on where you are on the planet).

The problem is that the magnetic field of the Earth is fairly weak on the surface. That is why a compass needs to have a lightweight magnet and a frictionless bearing. Otherwise, there just isn't enough strength in the Earth's magnetic field to turn the needle.[54] The question is how do animals sense the magnetic field and can robots duplicate the sensing methods.

[54] http://science.howstuffworks.com/compass1.htm

DSTL DATA SHEET 16.6-7. INTELLIGENT NAVIGATION ALGORITHMS

Technology Parameter(s)	In the next 5 to 10 years, the following will have the potential to significantly enhance military capabilities: 1. Ability to process real-time data using knowledge based system for real-time decision making for autonomous navigation system.
Critical Materials	Low power optical sensors. Micro-energy source over long time periods. Lightweight materials and high-torque miniature motors.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Data fusion of biological navigation sensors to meet technology parameter.
Major Commercial Applications	Commercial robotics.
Affordability Issues	Continued research necessary. Miniaturization of sensors required for next generation.

BACKGROUND

Intelligent navigation algorithm integrates or fuses biological navigation sensors and information to navigate a robot or unmanned vehicle through a complex and changing environment.

An illustration of data fusion is given in Figure 16.6-2 by the human system, which calls upon its different senses to perceive its environment. Like human sensors, the robot sensor will acquire information on sight, smell, touch, hearing, and taste. The acquired data are processed within the brain (computer). To do so, the brain (computer) will use other sources of information: its memory, its experience and its a priori knowledge. Calling upon intelligent algorithms, its reasoning capabilities, the brain "fuses" all this available information to perform deductions, to produce a representation of the environment and to order action.

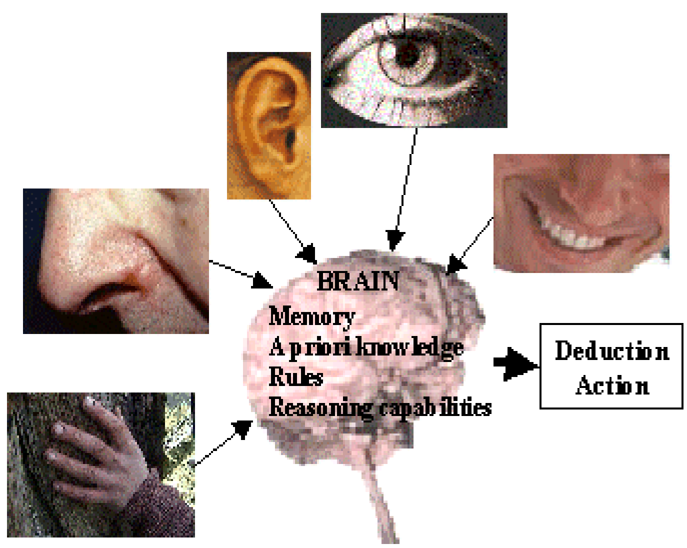


Figure 16.6-2. The human brain and perception system are as an example of the fusion process. (Source: http://www.data-fusion.org/article.php?sid=75.)